

Volume VI

SCIENTIFIC PAPERS OF C V RAMAN

**FLORAL COLOURS
AND VISUAL PERCEPTION**



Volume VI of the *Scientific Papers of C. V. Raman* contains the work Raman did in the last decade of his life. It also contains the charming monograph he wrote entitled the *Physiology of Vision*. Raman brings out the important point that the characteristics of human vision which play an important role in the perception of colour are as important in deciding a quality of a gem or a mineral as its optical properties. A simple method is given by which one could actually view one's own retina and explore its behaviour under various spectral excitations. Raman studies in detail the remarkable but not too widely known faculty of the unaided eye to recognise polarized light and also locate its plane of polarization. Raman investigates the incredible power of the eye to discriminate colours differing by as little as 10 \AA . Raman is interested in the relationship of brightness and colour, particularly the colours of nebulae viewed through small and large telescopes. He describes simple demonstration experiments to measure the intensity at which colour perception is lost for different colours.

(continued on inside flap)



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Scientific Papers of

C V RAMAN

Volume VI

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AND
VISUAL PERCEPTION**



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FLORAL COLOURS
AND
VISUAL PERCEPTION

Edited by
S Ramaseshan



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which one could actually view one's own retina. The observer views a brilliantly illuminated screen, holding before his eye a colour filter (which absorbs completely a limited region of the spectrum while transmitting the rest of it). When the filter is suddenly removed, he sees a highly enlarged view of his own retina (that too in colour) projected on the screen, displaying the response of different areas of it to the incident light. By using a series of filters transmitting different wavelengths, Raman could explore the behaviour of *his* retina under various spectral excitations.

Raman also studied in detail a remarkable but not widely known faculty—namely that the unaided eye is not only able to recognise polarised light but can also locate its plane of polarisation. Sky-light exhibits a high degree of polarisation when observed in a direction transverse to the rays of the Sun. When one views this region of the sky one sees the image of a cross, a dumb-bell shaped bluish brush along the direction of maximum polarisation, and a bright yellow brush of light perpendicular to it. Raman investigated this phenomenon by looking at the spectrum from a diffraction grating with a polaroid in front of it. From the direction of the brush and its response to colour, the orientation and the optical characteristics of the dichroic molecules in the visual pigments were deduced.

Raman did a series of experiments (some of them a repetition of earlier ones) and found that the eye could discriminate colours corresponding to wavelengths differing by as little as 10 \AA . Younger eyes could perceive the difference in colour between the D_1 and D_2 lines of sodium which are separated by just 6 \AA . This established that the transference of radiational energy to the sensing mechanism is a very rapid process not greatly influenced by the thermal agitation of the medium. (If it were, he reasoned that the discrimination could not be finer than $20\text{--}25 \text{ \AA}$ in the yellow).

Raman was interested in the relationship of brightness and colour. He was familiar with the appearance of nebulae as viewed by a seven-inch telescope which was available to him in Calcutta—faint indistinct patches of light with no colour. During a visit to California, he viewed the same objects through the 60-inch and 100-inch telescopes of Mt Wilson Observatory near Pasadena. He recounted vividly that the Ring nebula in Lyra exhibited flaming colours changing progressively from the external edge of its ring to its inner margin while the great nebula in Orion was a blazing area of variegated colour determined by the line emission of the gases of which it is composed. Obviously, the total energy of the light beam which is perceived not only increases the brightness but also considerably affects the sensation of colour. He did set up some simple experiments to demonstrate and measure the intensity at which the colour perception is lost for different colours.

Scintillation of stars

Perhaps the most intriguing observation he made during this period concerned a new type of “twinkling” of stars due to the statistics of photons striking the retina. It would not be possible to perceive a star steadily as a point of source of light unless the stream of light corpuscles reaching the particular spot on the retina is continuous and of sufficient strength. Failing this one can expect to perceive the star only by fits and starts depending on the statistics of the arrival of the photons. This picture of fluctuating luminosity would be exhibited most clearly by the fainter stars which are just on the borderline of visibility and would be less evident as the star goes up in the scale of luminosity. This quantum scintillation is altogether different from the well-known phenomenon of the scintillation of stars which has its origin in the local variations of refractive index in the atmosphere. This classical effect is exactly the same for bright and faint stars though naturally more easily observed in the former case. Further the elevation of the star from the horizon has a noteworthy influence. Raman made observations on stars high up in the sky on clear calm nights when the brighter stars in that vicinity did not exhibit variations in intensity. The fluctuating intensity was most obvious when two or more very faint stars fairly close together were viewed and their relative luminosities constantly compared. He found that these were continually changing and attributed this to photon statistics.

In this connection, it may be mentioned that Raman clearly set out in qualitative terms the presently accepted ideas on the conventional scintillation or twinkling of stars. He was convinced that only by invoking wave optical principles could this phenomenon be explained. The plane wave-front of light coming from a distant star gets randomly corrugated by the changes of refractivity accompanying density variations in the atmosphere. According to Raman one has to consider the diffraction effects of this ever-changing randomly corrugated wave front to understand the scintillation and other associated phenomena completely.

While considering the deceptively simple question as to why one was able to see the Milky Way in the sky with the naked eye, Raman set up many experiments to illustrate some strange characteristics of human vision. For example, when a wire mesh was held at the distance of distinct vision and viewed against a bright background, the apertures in the mesh through which the light passes can be perceived—well-defined and clearly separated. As the illumination is progressively decreased a stage is reached when the independent aperture areas cease to be visible and the entire mesh appears as a uniform field—but exhibiting a noticeable enhancement of fluctuations in the brightness over its area. These fluctuations increase conspicuously as the illumination is further reduced.

Raman had devised many such beautiful experiments and evolved many empirical theories to explain the perception of light and colour. He personally felt that his contributions to this field were important—as important as those he had made to light scattering. But other workers in this very complicated field were of a different view. Experimenters had introduced sophisticated microprobes into the eyes of living animals and combined these with very clever electronics to investigate the visual process. They felt, quite justifiably, that Raman's elementary experiments, however basic they appeared, were too simplistic for this complex field. Thus, his work remained largely unnoticed. Nevertheless many of Raman's simple observations may not yet have found a satisfactory explanation.

The years of depression

The remarks made so far describe Raman's scientific preoccupations in the last decade of his life. But they do not give a full picture of either his internal or external circumstances to which we now turn.

Many things happened at this time in his Institute and in the country which affected Raman greatly. The half a dozen graduate students whom he had handpicked to work at his Institute began to leave. By 1960 all of them had gone, and he chose not to take any more and (except for two assistants) he was almost all alone. It was then that Raman became a recluse, literally isolating himself by building high walls round his Institute discouraging visitors. He passed through a period of deep depression. He appeared to be in agony, to say the least.

Much of his torment must have sprung from his view of things happening in the country. It seemed to him that scientific administrators, not believing that there was sufficient strength in the country for science to grow, looked more and more outside for inspiration. The policy seemed to be that expenditure (however indiscriminate) would automatically further the progress of science and technology. He felt that the universities, which till then identified and generated talent, were denuded and desertified by the exodus of scientists and teachers to better paid positions in large, impersonal Government laboratories. Quantity appeared to be mistaken for quality. His attitude towards everyone—especially the Government—became one of suspicion and cynicism. But there were undoubtedly other causes for his depression at a much more personal level. Was it that once his students had left, he lacked the stimulation of discussing science with the young? Or was it because he finally sensed the decline of his creative powers? Or was it just the physiological process of ageing? One does not know.

Flowers and children

It was at this juncture that Raman rediscovered as it were the marvels of flowers and children. It was his interest in colour that made him look at flowers again—

for what better material was there which displayed such incredible variations of colour and hue to delight the human eye? Raman was always ardently interested in gardens and gardening. He personally planned, supervised and planted hundreds of flowering and avenue trees at the Indian Institute of Science for which it is now justly famous. When he set up an Institute of his own, the land had not a blade of grass on it and no water was available. He contoured the land so that not a drop of rain drained out and made it a veritable garden by planting many beautiful trees and flowering bushes. He had 168 rose plants in his Institute which he tended with personal care. He studied the spectra of the petals and extracts of hundreds of species of flowers. His Institute became a riot of colour and his laboratory exuded the aroma of a perfumery. When any lady visited him, he presented her with a magnificent bunch of flowers (on which he had experimented) and she thought that the Grand Old Man of Indian Science had chosen her specially for this honour! Twice every year—on January 26th and August 15th—he was at the historic Lal Bagh at the flower show examining the exhibits with his famed pocket direct vision spectroscope—himself attracting a greater crowd than the flowers!

And then he invited children to come. First there was a trickle, then almost everyday he was seen taking school children and college students round his Institute—regaling them with stories, teaching them science, making them observe things in nature, chiding them for not recognising the familiar objects that surrounded them—be they trees, plants, minerals or rocks—pointing out to them the exquisite beauty of each, showing them his precious gem and mineral collections, demonstrating many acoustical and optical phenomena so familiar to him, testing them for colour blindness, using their young eyes for spectral discrimination experiments. He asked smaller groups to visit the Institute in the evening and after nightfall he showed them the haloes of the moon, and through his 5-inch telescope, the mountains of the moon, the rings of Saturn, the moons of Jupiter and of course the great Orion nebula. The Institute was filled with the laughter of children, following old Raman from place to place. His spirits revived, his joy in doing science was restored and the verve he always felt as a teacher came back to him.

The end

On 2nd October 1970, he gave his last Gandhi Memorial Lecture *On the cochlea and the perception of sound*—(was he thinking of changing his field again?). For the first and only time in his life he asked of his large audience permission to answer their questions sitting down. At the end of October he collapsed in his laboratory, the valves of his heart having given way. He was moved to hospital and the doctors gave him four hours to live. He survived and after a few days refused to stay in hospital as he preferred to die in the gardens of his Institute surrounded by his flowers. When he was told that there was little chance that he could lead a

normal life and that he might have to spend it in bed, he refused medication since he would not care to live in the horizontal position.

On the 19th of November, two days before he died, he told a former student who was present, "Do not allow the journals of the Academy to die, for they are the sensitive indicators of the quality of science being done in the country and whether science is taking root". He then gave his vision of the future of his Institute:

"This Institute was created by me in 1948 to provide a place in which I could continue my studies in an atmosphere more conducive to pure research than that found in most scientific institutions.

"To me the pursuit of science has been an aesthetic and joyous experience. The Institute has been the haven where I could carry on my highly personal research.

"This personal character of the Institute should obviously change after me. It must blossom into a great centre of learning embracing many branches of science. Scientists from different parts of India and all over the world must be attracted to it.

"With its beautiful gardens, large libraries, extensive museums, I feel that the Institute offers a perfect nucleus for the growth of a centre of higher learning.

"Science can only flower out when there is an internal urge. It cannot thrive under external pressures. Fundamental science cannot be driven by instructional, industrial, governmental or military pressure. This is the reason why I decided as far as possible not to accept money from Government.

"I have bequeathed all my property to the Institute. Unfortunately this may not be sufficient for the growth of this centre of learning. I shall therefore not put it as a condition that no governmental funds should be accepted by the Institute. I would however strongly urge taking only funds that have no strings attached."

The same evening he held a meeting of the Board of Management of the Institute, conducted the proceedings from his bed, and when it concluded he dictated the minutes. He died peacefully early in the morning of the 21st of November, 1970.

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THE PAPERS

Light, colour and vision*

SIR C V RAMAN

Our eyes enable us to perceive the world around us, and they are, therefore, amongst our most precious possessions. What they accomplish is such a familiar experience that we cease to be conscious of the remarkable nature of the services which they render. I propose, in this lecture, firstly, to draw your attention to some of the outstanding features of our visual powers, and then to recount to you how they have been sought to be explained. The subject is so extensive in its scope that I cannot hope in the course of an hour's lecture, to do more than sketch very briefly, the explorations that have been made in this field of knowledge in past years and continue to be made at the present time.

Surveying the facts of visual experience, we may group them under three heads: firstly, we may remark upon the enormous range of the intensities of light to which the eye can adapt itself and yet function with comfort. From the brightest sunshine the dim starlight of a clear but moon-less night is a step-down in intensity by a factor of a hundred million, but one can nevertheless see well enough in either case, to keep to the path on a countryside walk. Indeed, the measurements, which have been made of the power of the eye to detect feeble light have shown that for very brief exposures, the human eye is several thousand times more sensitive than the fastest photographic emulsions so far produced. Secondly, we may remark upon the power of our eyes to adjust themselves for viewing objects which are either far or near, upon their power to judge the form and distance of the objects appearing in the field of vision, and to estimate their positions relatively to each other, as also to detect their movements. Then again, when attention is fixed on any limited area in the visual field, our eyes can perceive and recognize very fine details. Thirdly, we may remark upon the ability of our eyes to recognize and distinguish the characters of an illuminated object which may be described respectively as its brightness, its hue or colour, and the degree of saturation or purity of that colour. If all these three attributes are taken simultaneously into consideration, the number of possibilities between which our eyes can discriminate is extremely large.

The incidence of light from external objects on our eyes and our perception of these objects are the two ends of a connected set of processes: firstly, the

*Gandhi Memorial Lecture delivered on Friday, the 2nd October 1959, at the Raman Research Institute, Bangalore.

functioning of the eye as an optical instrument which forms images of external objects on the retina; secondly the functioning of the retina as a receptor of radiant energy; thirdly, the transmission of the messages originating at the structures of the retina to the visual centres in the brain, and finally the integration of the messages received from the retinae of both the eyes into a visual picture exhibiting various characteristic features, viz., form, depth, detail, brightness, colour, and movement. The importance of the role which binocularity plays in the phenomena of vision needs to be stressed. It is very strikingly illustrated by the known facts of colour vision; when a picture of an object printed in complementary colours in stereoscopically displaced positions is viewed through complementary filters placed before the two eyes, one perceives a single picture in relief, but exhibiting no colour whatever.

2. The eye as an optical instrument

Leonardo da Vinci was the first to propose a rational theory of the functioning of the eye. He compared it with that of the *camera obscura* and assumed that an image rendered sharp by the lens was formed on the internal cavity of the eye. Indeed, it is the case that the eye is built in several respects like a photographic camera. It is approximately spherical in shape, and is covered by a fibrous tunic which is white and opaque for the most part, but has a transparent protuberance in front which is of greater convexity than the rest. These two parts of the eye are known respectively as the sclera and the cornea. The darkening of the interior necessary in a camera is secured by the presence of the chorioid coat which is a membrane traversed by numerous blood vessels and abundantly pigmented. The chorioid clings closely to the sclera and absorbs the unwanted rays. Against the inner surface of the chorioid coat lies the part of the retina which is sensitive to light. A further analogy with a camera is provided by the eyelids, which, acting like a shutter, can be closed to exclude light. Likewise, when light is admitted, it is regulated in amount by the variation of the size of the pupil which corresponds to the variable aperture of a photographic camera.

The interior of the eye is not empty, but is filled with transparent media known as the aqueous humour and the vitreous body which fill respectively the front and the back of the cavity. Their refractive indices (1.336) differ very little from that of pure water. Behind the iris lies the lens of the eye. Both of its surfaces are convex, the front less so than the rear. The refractive index of the lens varies from the centre to the periphery; its effective value is 1.42. Since however, the lens is immersed in a medium of which the index is 1.336, its converging action on the light is greatly reduced thereby, and only supplements that produced by the front surface of the cornea. The principal function of the lens is to enable the eye to accommodate itself for near or distant vision as required. This is brought about by the action of the ciliary muscles on the capsule which is an elastic membrane

completely enclosing the lens; the force thus exerted on the material of the lens enables the curvature of its front surface to be increased for near vision as compared with the normal state of the eye when viewing distant objects.

The shape of the eye-ball is maintained by the action of what is known as the intra-ocular pressure, viz., the hydrostatic pressure of the fluid filling the cavity of the eye. Fresh fluid is continually added to the aqueous humour and is continually drained away from it into the blood stream by a complex arrangement which is so regulated that the pressure of the fluid within the eye remains roughly constant. Since, as already remarked, the external surface of the cornea plays the leading role in the work of the eye as an optical instrument, it is not surprising to find that provision exists for protecting the corneal surface and maintaining it in good condition. This, indeed, is the function of the eyelids and the lacrimal apparatus. The periodic blinking of the eyes serves the purpose of cleaning and wetting the cornea.

The effective functioning of our eyes is to a very great extent dependent upon certain accessory structures associated with them. The eye-ball is located within the cavity known as the orbit and its movements are controlled by three pairs of muscles which enable the eye to be directed towards any particular object in the field of vision. The construction of the eye makes it possible to have a very large angular field of vision. This, for each eye separately, is about 160° laterally and 120° vertically, and for both eyes together, somewhat more than two right angles from left to right. It is, of course, not to be expected that the image of external objects formed on the surface of the retina would everywhere be sharply focussed. Indeed it is only over a very small fraction of the whole field of view that the image on the retina is well defined and sharp. When we direct our eyes towards an object, we make use of this well-defined part, which, as we shall see presently, falls on the region of the retina which is best equipped for the discrimination of fine detail in the image.

A question of some interest is the reason why the effects of chromatic aberration on our vision are scarcely noticeable in normal circumstances. The explanation is that the refractive media of the eye have very small dispersive powers. Further, the sensitivity of the eye to radiation exhibits a maximum spread over a narrow region of the visible spectrum. This circumstance would tend to minimise any visible manifestations of chromatic aberration. They can however be observed when a small, bright source of light is viewed through a colour filter which transmits only the two ends of the visible spectrum, viz., red and violet respectively.

3. The structure of the retina

The retina is a delicate membrane which is specially adapted for the reception of light stimuli. In the fresh state it is soft, translucent, and of a purple tint, owing to

the presence of a colouring material named rhodopsin or visual purple. Near the centre of the retina there is an oval yellowish area, named the *macula lutea* where the visual sense is most perfect. This shows a central depression which is termed the *fovea centralis*, where the retina is exceedingly thin, some of its layers having practically disappeared, and the dark colour of the chorioid is distinctly seen through it. About three millimetres to the nasal side of the *macula lutea*, the optic nerve pierces the retina at the optic disc which has a diameter of about 1.5 millimetres. The centre of the disc is pierced by the central artery and the vein of the retina. The optic disc is insensitive to light and is termed as the blind spot.

The retina itself consists of several layers of cells. The first is the pigmented epithelium which is firmly joined to the inner surface of the chorioid coat. Next comes the retina proper or the visual layer containing the receptor cells and their nuclei. The receptors are recognized as being of two kinds known respectively as the rods and the cones. They both consist of elongated cells which point towards the chorioid coat, and the light entering the eye has accordingly to pass through the remainder of the retina to reach them. The impulses originating at the visual layer are then transmitted to the optic nerve through the outer layers termed collectively as the bipolar and ganglionic layers. The outermost layer of the retina in contact with the vitreous body is the *stratum opticum*. It consists of the nerve fibres formed by the expansion of the optic nerve over the surface of the retina. They are connected with the visual cells through the bipolar and the ganglionic layers. The human retina contains some six million cones and over a hundred million rods, whereas the optic nerve contains only some 8,00,000 nerve fibres. It follows that some tens and sometimes even hundreds of receptor cells must be connected to a single ganglion cell by way of the bipolars. An exception, however, appears to exist in respect of the *fovea centralis*. Here there are no rods and the cones are longer and thinner than in the other parts of the retina. Each cone in this area is connected separately by way of a monosynaptic bipolar to an individual ganglion cell and this enables it by means of the corresponding fibre of the optic nerve (which is simply the axon of the ganglion cell) to act individually at the cortical centre. It is in this manner that the high degree of visual acuity or power of discrimination possessed by the central area of the retina has been explained.

4. The duality of the visual process

When a person quits the sunshine out of doors and enters a dark room, he can see nothing at first. His eyes then slowly adapt themselves to darkness, and in about half an hour, he becomes fully sensitive to the faint illumination present and can distinguish the various objects around. Conversely, when a person who has been long in darkness comes out into the light, the reverse process of adaptation to a high level of illumination takes place, but this is a much quicker process. These

and other well-established facts indicate that the human eye possesses two retinæ interlaced with each other. One is a day-retina, which has a low sensitivity to light, can perceive differences in colour, and possesses (at least in its central regions) a high degree of visual acuity. The other is a night-retina which has a high sensitivity to light, but lacks appreciation of differences in colour and exhibits a very low visual acuity. So striking are these differences that it is found convenient to give the name of photopic vision to the function of the day-retina and scotopic vision to that of the night-retina.

As remarked above, the sensitivity of the eye to light differs enormously in photopic and scotopic vision. Its variation with wavelength over the visible spectrum has been investigated for both types of vision. A pronounced maximum somewhere in the middle of the spectrum is exhibited in both cases. But the positions of this maximum differ notably, being $557\text{ m}\mu$ for photopic and $510\text{ m}\mu$ for scotopic vision. If the two curves of spectral sensitivity are drawn in such manner that the ordinates of the maximum are the same in both, the photopic curve lies well above the scotopic in the red, orange, and yellow regions of the spectrum and well below it in the blue and violet regions. This difference is responsible for the well known and easily observed Purkinje phenomenon which may be stated briefly thus: the relative brightness of two objects, coloured red and blue respectively, changes in a most striking fashion when the light which illuminates them falls off from a high to a low intensity.

It is reasonable to ascribe photopic vision to the activity of the cones in the retina as receptors of light, while scotopic vision represents the functioning of the rods. The characteristic differences between the two types of vision in respect of sensitivity and acuity can be explained on this basis. As already stated, the rods in the retina are far more numerous than the cones and their number is enormously larger than the number of separate nerve fibres connecting the retina with the cerebral centre. Rod vision, therefore, arises from the co-operative effect of a great many of them functioning together and this would, at least in part, explain its characteristic features. The absence of rods in the foveal region of the retina and their presence elsewhere would indicate that sources of light which are too faint to be seen when viewed directly would be visible in averted vision. This, indeed, is a fact of observation, as for example when faint groups of stars are looked for at night in the sky.

5. The phenomena of colour vision

Colour plays such an important role in so many different types of human activity that it has naturally been the subject of intensive investigations from many different points of view. The sensations produced by coloured light may be described as presenting three distinct subjective characters, viz., brightness, hue or colour

proper, and the degree of saturation or purity of the colour. The pure colours we are acquainted with are the colours exhibited by a well-resolved spectrum. These range from red to violet but the eye can distinguish a great many different colours between these extremes. The question naturally arises how the colours we meet with in nature or can be artificially produced, are related to the pure spectral colours.

We may begin by stating a few well-established facts of observation. By superposing appropriate amounts of a pure spectral red, say $700\text{ m}\mu$ and a pure spectral green, say $546\text{ m}\mu$, it is possible to reproduce any other colour appearing in the spectrum within this range of wavelengths. Then again, for any given spectral colour lying in the region between the red and the yellow, it is possible to choose a corresponding spectral colour lying in the range between greenish-blue and violet so that appropriate amounts of the two when superposed would result in a pure white. On the other hand, it is not possible to find a spectral colour complementary to radiations in the green region of the spectrum. Then again, by the super-position of spectral colours lying respectively at the red and violet ends of the spectrum, a series of colours are produced which are not observable in a pure spectrum, viz., the purples.

Finally, it may be remarked that by mixing *three* selected spectral colours in definite proportions, we may match any desired colour sensation. This is the fundamental law of colour vision which has however to be understood in a special sense, viz., that in certain cases the addition is to be replaced by a subtraction. Why this is so can be readily understood if we represent the three selected spectral colours by the vertices of a triangle and the colours obtained by superposing them by points inside the triangle. Taking the three selected spectral colours to be $700\text{ m}\mu$ (red), $546\text{ m}\mu$ (green), and $436\text{ m}\mu$ (blue), pure white would correspond to a point at the centre of the triangle, while other colours drift away from the centre in a direction represented by the dominant hue and to an extent which expresses its purity or saturation. But colours closely approximating in purity to the colours lying between the green and violet in the spectrum would lie outside such a triangle. Hence one would have to add to the colour under study a suitable amount of its complementary and thereby diminish the saturation or purity of the resultant to make it the same as the mixture of two colours compared with it.

The foregoing statements refer to the facts of colour vision as normally observed. Anomalies of colour vision are however exhibited by certain individuals, and these have been very thoroughly investigated by reason of their interest in relation to theories of colour vision. Persons whose colour vision is anomalous may be classified into three groups, viz., anomalous trichromats, dichromats, and monochromats. Anomalous trichromats are those who need, in general, three component stimuli to match any given colour, but their proportions are different from those for normal observers. Dichromats are those who require only two component stimuli; while monochromats are subjects who see only variations of brightness and are unable to recognize any colour.

6. Photochemistry of the retina

The principal characteristic of the reaction of the retina to light is its extreme selectivity as regards wavelength. In view of this, the only reasonable explanation of the sensitivity of the retina to light that has been proposed is one based upon the photochemical action of light. In other words, light is absorbed by a coloured substance associated with the receptor cells and induces a change in the substance; this in its turn sets up or gives rise to an electrical displacement or potential which is taken up and transmitted by the nerves as an impulse to the cortical centre. For such a theory to be sustainable, the photosensitive substance has to satisfy a number of requirements. It must be stable in the dark and after being altered or destroyed by light should be capable of being regenerated so that the receptor could continue to be light-sensitive.

As mentioned earlier, the retina in the fresh state exhibits a purple tint. But when exposed to light it becomes clouded, opaque, and bleached. Thus it is natural to assume that the colouring matter present in the fresh retina known as rhodopsin or visual purple is the photosensitive substance which enables the transformation of light into some other form of energy capable of acting directly on the nerves. A substantial proof of the correctness of this view came to hand when the light-absorption curve of human visual purple was determined and its resemblance to the scotopic curve of luminous efficiency in the spectrum was revealed. In other words, rhodopsin or the visual purple is indicated as the agent responsible for the activity of the rods in the retina as receptors of light radiation. The loss of the sensitivity of the eye to weak illumination in bright daylight and its restoration when the subject remains in the dark for long periods is explained on the basis that the exposure to strong light bleaches out the rhodopsin and that this is regenerated in darkness after a sufficient period of time.

Quite naturally, therefore, one is led to suppose that the sensitivity of the cones in the retina also arises from the presence of other photosensitive pigments in them. Experimental evidence supporting this view has been adduced by W H Rushton in a recent remarkable investigation. He has developed a technique for measuring the pigment present in the fovea by analyzing the light reflected from it and observed in an ophthalmoscope. Observations were made by him with normal trichromatic individuals and as also with a dichromat who was rather insensitive to red light. It was found that the fovea on exposure to bright light bleaches and darkens again during the next few minutes. Evidence is forthcoming from the observations that the normal fovea contains two visual pigments, one of which is green-sensitive and the other is red-sensitive; the former alone was found to be present in the fovea of the dichromat.

On the sensations of colour and the nature of the visual mechanism*

SIR C V RAMAN

1. Introduction

Light and colour play a fundamental role in human life and activity. We are therefore naturally led to ask various questions concerning them and the sensations which they evoke. How do our eyes perceive light? Why is it possible for our eyes to discriminate between different kinds of light, thereby enabling us to label them with distinctive names? It is proposed in this address to consider these and related questions and endeavour to answer them.

We may usefully remind ourselves at the outset that the physical phenomena exhibited by light may be divided into two classes. The first class includes various optical effects, such as reflection, refraction, interference and diffraction. In all these effects, we are concerned with the propagation of light considered as wave-motion in space. In the other class of phenomena which includes the emission and absorption of light, fluorescence and the photoelectric effect, we are concerned with energy transfers and energy transformations. Such phenomena find a satisfactory explanation only when we consider light to consist of discrete units or quanta of energy. Accordingly, they fall within the scope of the quantum theory of radiation.

The dual role played by radiation is also evident in the functioning of our visual organs. The formation of well-defined images on the retina of our eyes is clearly a phenomenon falling within the range of wave-optics. But it is clear that the visual mechanism by which we perceive light and colour lies outside the scope of wave-optics and should be considered and investigated from the standpoint of the quantum theory. This is the point of view adopted and developed in the present address.

We shall begin with a brief survey of the facts of the subject.

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2. The perception of light and colour

The sensations excited by light are of two distinct kinds, luminosity and hue or colour. Though they are essentially subjective in nature, they can be brought within the scope of physical definition and measurement by inter-comparison and equalisation of the luminosity or colour of two adjacent illuminated areas. This is indeed the procedure on which visual photometry and colorimetry depend. The human eye can function over an enormous range of intensities. But at the lowest levels of illumination, e.g., in night-vision, the eye can perceive only differences of luminosity but is unable to appreciate colour. At such levels also, it is insensitive to the light which is normally perceived as red in hue. For the proper appreciation of colour, it is necessary to work at levels of illumination which are fairly high and which have to be employed so that, in other respects as well, our eyes can function efficiently. Colour and colour differences are also best observed and studied in direct vision, in other words when the eyes are turned to view the objects under observation and their images are formed at or near the fovea centralis on the retina. Colour can be perceived also in averted vision up to fairly large angles, but it does not then lend itself to any precise comparison and measurement.

Two kinds of light are of special importance. One of them is white light, in other words light exhibiting no perceptible colour. The other kind of light is that which appears at various points in a well-resolved spectrum. The colours ordinarily met with may be described as a mixture of white light with some particular spectral colour, the result of such mixture exhibiting the same hue as the pure spectral colour but in an unsaturated or diluted form. This way of describing and classifying colours may be made completely comprehensive, if besides the pure spectral colours, we also consider the colours which are not observed in the spectrum but which may be obtained by superposing light from the two ends of the visible spectrum, viz., red and violet, in various proportions. Taking the pure purples arising in this fashion together with the pure colours of the spectrum, we may say that all colours that come within the scope of colorimetry may be described as mixtures arising from the addition therewith of appropriate quantities of white light. It follows from what has been stated that our chief concern is with the subject of monochromatic colour vision. The results of colour mixture are a matter of secondary importance.

Conventionally, the colours of the spectrum are described as six in number. Actually, the normal human eye can discern in the spectrum not less than 150 distinct patches of colour which cannot be made to match one another in colour merely by adjusting their intensities. Except at the two extreme ends of the visible spectrum, a change of 50 \AA in wavelength is more than sufficient to result in an observable differences in colour. Indeed, a much smaller difference suffices over a large part of the visible spectrum. The change in wavelength needed for an observable change of colour has been determined over the whole range of the

visible spectrum by several investigators and the hue-discrimination curve thus drawn shows some remarkable features. At four points in the spectrum, at the wavelengths (in Å units) 4400, 4900, 5900 and 6300, it dips down and the change in wavelength required for a perceptible change of colour reaches low values. The wavelengths 4900 and 5900 are specially conspicuous in this respect, a change of 10 Å in wavelength sufficing to produce an observable change of colour, while at intermediate wavelengths it is larger, rising to 20 Å at 5400 Å. The dips in the curve at 4400 and 6300 are less conspicuous, the minimum change of wavelength needed in their neighbourhood being about 20 Å, while at the intermediate wavelengths 4600 and 6200, it rises to 30 or 40 Å.

3. The physical basis of colour

The facts of observation set forth above lead us to ask ourselves the question, what is the physical basis of colour? In other words, what is it that enables the eye to distinguish between various kinds of monochromatic light? The answer to this question has clearly to be sought for in the known physical properties of light itself. The physical characters which distinguish one beam of monochromatic light from another are firstly, the quantity of energy traversing unit cross-section of the beam per unit of time and secondly, the magnitude of the individual energy-quanta. The subjective characters, which enable one such beam to be distinguished from another, are the luminosity of a white surface on which the beam falls and the colour which the surface then exhibits. It is a natural inference that the physical and subjective attributes of the light are related to each other in a fundamental way, viz., total energy flow with luminosity, and the magnitude of the individual quanta, with colour. Indeed, if it were not so, photometry and colorimetry would be meaningless exercises of human ingenuity.

We are thus led to conclude that our power to distinguish between different monochromatic radiations by the colour sensations which they excite is a consequence of the fact that light consists of distinct units or quanta of energy and that these units are of different magnitude, increasing continuously from one end of the spectrum to the other. It follows from this again that the nature of the visual mechanism is such that it enables these differences to be perceived. We may also infer that the variation in the power of the eye to detect changes of colour in various regions of the spectrum is a consequence of the special features of the visual mechanism.

4. The nature of the visual process

A difference of 10 Å in the wavelength of monochromatic light represents a change of only two parts per thousand in the magnitude of the individual light-

quanta of which it is composed. We may well ask ourselves, what is the nature of the visual process or mechanism which makes it possible for our eyes to appreciate or detect such a very small change?

The anatomy of the retina makes it clear that its function is to receive the incident light energy and to transform it into impulses (presumably of an electrical nature) which travel along the optic nerve to the cerebral centres. If the distinguishing character of the light, viz., the magnitude of the energy quanta of which it consists, is to reach the cerebral centres, it is clearly necessary that the energy of the quantum incident on the retina is in the first instance completely absorbed and is then transferred completely and immediately to the nervous system. Any additions to or subtractions from the energy would result in an alteration in the characters of the excitation and therefore also of the resulting sensation. The latter, in such circumstances, may indeed be the perception of light but it would lack the specificity indicated as necessary by the facts of colour perception. For the reasons stated, we may exclude from consideration visual mechanisms which assume photochemical changes to occur involving absorption of energy by the retina, and confine ourselves to the simplest possible process, viz., the quanta of light energy falling on the retina are absorbed and the energy absorbed is immediately transferred to the nervous system, the absorbing centres then returning to their original state. The fact that the normal human eye can perceive colour throughout the visible spectrum without a gap indicates that it is adequately covered by the absorption spectra of pigments present in the retina, the molecules of which can function in the manner indicated.

The level of illumination at which the colour sense is at its best is fairly high, in other words there is plenty of light which could enable the process contemplated to operate. Hence, even if only a fraction of the number of energy-quanta incident on the retina are absorbed and then passed on to the nervous system, the resulting effect would be of adequate magnitude. Moreover, as we have seen, the pigments which act as absorbers of light return immediately to their normal states and can therefore function repeatedly. In other words, they are not expendable. It is evident that in these circumstances, small quantities of the absorbers would suffice, so small that their presence in the retina need not be very conspicuous. For their functioning, it is clearly necessary that the absorbing substances are diffused through the material of the retina. Hence, they should be either themselves proteins or else substances of biological origin which can co-exist with the proteins and other substances present in the retina.

5. The retinal pigments

Amongst the products of biological activity that exhibit absorption spectra in the visible region of the spectrum, the carotenoids and the blood pigments are of

special importance. The carotenoids are so named, as they are derivatives of the hydrocarbon carotene, the chemical formula of which is $C_{40}H_{56}$ and which has several isomers, the most important being α -carotene and β -carotene. The carotenoid pigment with which we are specially concerned here is dihydroxy- α -carotene whose chemical formula is $C_{40}H_{56}O_2$. Together with the isomeric dihydroxy- β -carotene (zeaxanthin), it forms the principal constituent of the yellow pigment present in the yolk of the domestic hen's egg. It has also been identified as being responsible for the yellow colour of the region in the retina long known as the macula lutea and has been appropriately named as lutein, though the alternative name of xanthophyll is also to be found used in chemical literature.

It is of interest to note that the presence in the foveal region of the retina of a pigment which strongly absorbs blue light can be demonstrated in a simple manner. A cloudless sky is viewed for a few minutes through a filter of deep blue glass which transmits only the wavelengths of the spectrum smaller than 5000 \AA . If the filter is then suddenly removed and the sky viewed directly, an image of the fovea which can be recognized as such by its angular dimensions is seen clearly projected against the sky. The image, however, soon fades away.

Viewed in the ophthalmoscope, the retina appears of a rich red hue, which masks the colouration of the macula lutea. The latter can only be distinguished by using red-free light when it appears as an elliptic spot with the major axis horizontal. The red colour of the retina has itself been attributed to the selective diffusion by the choroid of the light which has penetrated the epithelial pigment of the retina, in other words of the light which has passed twice through the latter before it can re-emerge and be observed. Quite apart from the question of the sufficiency or correctness of this explanation, it has to be remarked that the retina is richly supplied by blood vessels which enter into the nervous layer and pass forwards through it, and from their branches give off a minute capillary plexus. The macula receives two small branches and also small twigs directly from the central artery. Though these latter do not reach the fovea centralis and the latter has therefore no blood vessels, the anatomical drawings indicate that the entire blood-supply system of the retina has been so contrived that its central region where vision is most perfect is completely surrounded by blood-rich material from which it could receive the blood-pigments necessary for its functioning. That the blood-pigments are powerful absorbers of light is indicated by the fact that blood is opaque to light and that oxyhaemoglobin can be spectroscopically detected in aqueous solutions as dilute as one part in a hundred thousand. As has already been remarked, no great quantity of a light-absorbing material is needed to enable it to function in the visual mechanism. In these circumstances, we are entirely justified in assuming that blood-pigments are present in the retina in sufficient quantity to function in the manner already explained and that they play a highly important role in the visual process.

6. The absorption spectra of the retinal pigments

Lutein: The absorption spectrum of lutein (xanthophyll) can be readily studied with the material obtained from the yolk of an egg. The pigment is completely transparent to all wavelengths in the red, orange, yellow and green regions of the spectrum. Its absorption is limited to the blue region in which three bands can be seen, of which the maxima are located at 4800, 4475 and 4200 Å, the first two being much more conspicuous than the third. The drop from complete transparency at 5200 to almost complete opacity at 4800 is rather abrupt; the steepest part of the spectrophotometer curve exhibiting this transition appears in the wavelength region around 4900 Å. The absorption by lutein diminishes notably as we approach the violet end of the spectrum.

Oxyhaemoglobin: The scarlet or oxygenated form of blood-pigment exhibits two clearly marked absorption bands, one in the yellow region of the spectrum centred at 5775 and the other in the green at 5385, the first of them being much sharper than the second. A graph exhibiting the transmission of light through an aqueous solution of oxyhaemoglobin shows a deep trough lying in the region of wavelengths between 5000 and 6000 Å, the two absorption bands mentioned above appearing at the bottom of the trough. The percentage of light transmitted rises very steeply on the side of longer wavelengths, the steepest part of the rise appearing in the region of wavelengths around 5900. At wavelengths greater than 6000 Å, the absorption is small, though remaining perceptible up to about 6800 Å. On the other hand, the transmission which is a maximum around 5000 Å diminishes again at still smaller wavelengths and indeed there is very little transmission below 4400 Å. However, by using very dilute solutions or very small absorption depths, the study of the transmission of light at the violet end of the spectrum reveals the presence of a powerful absorption maximum centred at 4145 Å, known as the Soret band.

Ferrohaemoglobin: The two absorption bands of oxyhaemoglobin at 5775 and 5385 are replaced in the case of its reduced form by a single diffuse band centred at 5575 which covers the entire region between them and also extends beyond them, though not very distinctly. In other respects, the spectroscopic behaviour of the two substances is nearly the same. The Soret band of haemoglobin has its maximum at 4250.

Ferrihaemoglobin: This pigment exhibits a marked absorption of light over the whole of the visible spectrum including the red end, in this respect differing markedly from the two other blood-pigments. At wavelengths greater than 6300, however, the absorption diminishes rapidly and becomes weak at the extreme red of the spectrum. Absorption maxima may be recognized which are centred at 6300, 5765, 5365 and 4995, the last-mentioned being very broad and diffuse. The maximum of its Soret band is located at 4060.

We may summarise the foregoing as follows:

A. Lutein is an efficient absorber of light in the region between 4900 and

4400 Å. It is wholly ineffective at wavelengths greater than 5000 but can absorb (though only feebly) wavelengths at and near the violet end of the spectrum.

B. Ferrohaemoglobin and its oxygenated form exercise a powerful absorption of light in the wavelength range between 5000 and 6000, with a resultant maximum centred at 5580 Å.

C. Ferrihaemoglobin has an absorption extending over the entire visible spectrum and differs from the other two blood-pigments in possessing a well-defined absorption band at 6300 Å.

No reference has been made above to the retinal pigment known as visual purple, since we are concerned here with the colour sensations experienced at normal illumination levels, in which, as is well-known, visual purple plays no role.

7. The luminous efficiency curve

A remarkable feature of the perception of monochromatic light by the eye is the manner in which its luminous efficiency varies with wavelength over the range of the visible spectrum. A highly pronounced maximum appears at a certain wavelength in the green region of the spectrum and on either side of it, the luminous efficiency falls off steeply. The wavelength of maximum efficiency observed with different individuals is found to vary from 5490 to 5700 Å, the average being 5576.

The most reasonable explanation of the fact stated above is that it is a consequence of the variation with wavelength of the strength of absorption of light by a pigment present in the retina which receives the energy of the light quantum and passes it on to the nervous system. In the preceding section, it has been remarked that ferrohaemoglobin has an absorption band of which the centre is located at 5575 Å. This agrees with the observed average for the wavelength of maximum luminous efficiency of the normal human eye. If its oxygenated form were the operative pigment, it would show two maxima at 5775 and 5385 respectively with a dip midway between them. But since the reduced form would also be present and its absorption band covers the region between the two bands of oxyhaemoglobin, the resultant would be a maximum at nearly the same position, viz., 5580. The agreement which thus emerges between the location of the absorption maximum of the blood-pigments and of the maximum luminous efficiency in the spectrum is scarcely a matter for surprise in view of the immensely important role that blood and its constituents play in the maintenance of life.

The observed form of the luminous efficiency curve indicates that two other pigments should be present in the retina which are effective absorbers respectively for wavelengths less than 5000 Å and greater than 6000 Å, in other words in the blue and the red regions of the spectrum. The former is evidently lutein and there is good reason for identifying the latter with the blood-pigment methaemoglobin,

more appropriately designated above as ferrihaemoglobin to indicate its chemical relationship with ferrohaemoglobin, the ordinary form of haemoglobin. Since the red cells in blood are provided with mechanisms both for the formation of ferrihaemoglobin by the oxidation of ferrohaemoglobin and for its reduction back to the ferrous state, there are good grounds for assuming the presence of ferrihaemoglobin in the retina where it is needed and has a specific role to perform.

8. Hue discrimination in the spectrum

The major features of the distribution of luminosity and colour in the spectrum can be ascertained in a very simple manner merely by viewing the white-hot straight filament of a tungsten lamp through a diffraction grating. It then becomes evident that the most luminous part of the spectrum is in the greenish-yellow region and that on either side of it the luminosity falls off unsymmetrically, in other words, more slowly on the side of longer wavelengths. The observable colour alters with change of wavelength but such change is most rapid at certain points in the spectrum, and relatively slow in the intermediate regions. In particular the change-over from blue to green and from yellow to orange is particularly rapid, while the change from green to yellow is quite gradual. The change from violet to blue occurs in a narrow region of the spectrum, and there are also indications that the change from orange to red is rather abrupt.

The facts stated above find quantitative expression in the hue discrimination curve which has been studied by several investigators. They receive a satisfactory explanation on the basis of the data regarding the retinal pigments and their spectroscopic behaviour. It was remarked earlier that lutein changes over from complete transparency to nearly complete opacity abruptly in the region of wavelengths around 4900 \AA . This, it may be remarked, is precisely the place where the hue discrimination curve dips down very steeply. Then again, ferrohaemoglobin changes over from almost complete transparency to nearly complete opacity in the region of wavelengths around 5900 \AA . This again is the wavelength at which the hue discrimination curve dips down to its lowest point. In other words, the change from blue to green is rather abrupt for the reason that lutein functions very efficiently at wavelengths less than 4900 but ceases to function at greater wavelengths, its place being taken over by ferrohaemoglobin. Similarly the change from yellow to orange is abrupt for the reason that ferrohaemoglobin functions efficiently at wavelengths below 5900 \AA but ceases to do so at greater wavelengths and its place is taken by ferrihaemoglobin. On the other hand, the transition from green to yellow is quite smooth for the reason that ferrohaemoglobin functions over the whole range under consideration. The minor features in the hue discrimination curve noticed in the blue and red regions can likewise be explained in terms of the striking changes with wavelength in the form

of the absorption curves of lutein and ferrihaemoglobin which are the pigments functioning in those regions.

9. The results of colour mixture

As stated earlier, the sensation produced by non-homogeneous light may be equated to that resulting from an admixture of white light with an appropriately chosen "pure colour", the latter term including the pure colours of the spectrum as well as the pure purples produced by the superposition of light from the extreme red and violet ends of the spectrum. This fact emerges from the numerous investigations on colorimetry made in the past, the results of which are embodied in the so-called chromaticity diagrams of which there are various forms. We shall here refer to and briefly describe the XYZ type of representation which at the present time is most generally accepted and used.

The XYZ chromaticity diagram takes the form of a closed figure which is roughly triangular in shape with a rounded vertex and a straight base which represents the line of pure purples. The rest of the perimeter of the figure represents the pure spectral colours arranged on it in a manner which will presently be stated. All observable colours (including white light) are represented by points lying within the closed figure, the point representing white light appearing somewhere near its centre. The pure spectral colours ranging from the extreme red end of the spectrum up to and including a part of the green up to 5350 \AA appear on one side of the triangle arranged on what is practically a straight line. The pure spectral colours from 5350 to 5050 \AA appear as the rounded-off vertex of the triangle. The third side of the triangle is a curved arc on which the spectral colours from 5050 \AA up to the extreme violet end appear. The wavelengths are however distributed on this arc very non-uniformly. Practically the whole of its length is taken up by the wavelengths from 5050 to 4600 \AA , while the rest of the spectrum from 4600 to 3800 (the extreme violet end) is compressed into a very short arc which forms the tip of the perimeter where it joins the line of purples.

The form of the chromaticity diagram as described above has a striking and indeed obvious relationship to the spectroscopic behaviour of the retinal pigments described earlier. The curved arc running from 5050 to the violet end of the spectrum is the region of wavelengths where lutein exercises a marked absorption, and it is therefore not surprising to find that practically the whole of the arc is taken up by the wavelengths at which such absorption is greatest. *Per contra*, lutein is completely transparent to all the wavelengths which appear on the straight line forming the other side of the triangle. This region is covered by the absorption spectra of the blood-pigments where such absorption is strongest, while the rounded-off vertex of the triangle represents the part of the spectrum in which the strength of their absorption falls off rapidly, as is shown by the absorption-curves themselves and is independently confirmed by the rapid drop in

the luminous efficiency of the spectrum between 5350 and 5050 Å. The form of the chromaticity diagram thus indicates that the three receptors contemplated in the trichromatic theory of vision may be identified respectively with the three retinal pigments lutein, ferrohaemoglobin (including its oxygenated form) and ferrihaemoglobin operating in their respective regions of absorption in the spectrum.

10. Anomalies in colour vision

The blood-pigment ferrohaemoglobin is readily oxidisable to ferrihaemoglobin, but such oxidation is ordinarily inhibited by the circumstance that it can form the molecular compound with oxygen known as oxyhaemoglobin which circulates through the body in arterial blood and is returned after de-oxygenation through the veins. Normally, therefore, ferrihaemoglobin is not present in human blood in any appreciable quantity, though in certain pathological conditions it is known to form a substantial proportion of the blood-pigment. The presence of ferrihaemoglobin as a receptor for colour vision in the retina must therefore be regarded as a special provision to meet the need for a pigment which has a strong absorption in the region of wavelengths greater than 6000 Å. The possibility therefore arises that the quantity of it in the retina may in certain cases be either greater or less than that normally present and that it may even indeed be totally absent in some cases. In the latter event, the person concerned would be red-blind. On the other hand, a deficiency would result in colour vision of the type known as protoanomalous, while an excess would result in deuteranomalous vision. In the former case, the result would be a closing up of the luminous efficiency curve away from the red so that its asymmetry of form becomes less pronounced. In the latter case the luminous efficiency curve would open out towards the red and its asymmetry of form become more pronounced.

As was remarked earlier, the dip in the hue discrimination curve normally observed at 5900 Å arises from the large fall in the strength of the absorption of light by ferrohaemoglobin which occurs in the region, while at greater wavelengths, the operative pigment is ferrihaemoglobin. If, however, the latter is not present in sufficient quantity, the change in hue with change of wavelength would be less rapid, in other words, the hue discrimination curve would move upwards. These results are in agreement with the ascertained facts of the subject.

The perception of light and colour and the physiology of vision—Part I. The mechanism of perception

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1. Introduction

Light, colour and vision play a role of fundamental importance in human life and much has been written about them from diverse points of view. Nevertheless, we do not find in the literature of the subject an acceptable answer to such a simple question as the following: How and why is it possible for us to distinguish by sight the different radiations emitted by a light source, such as the mercury arc for example, and name the colours we perceive? It is no answer to such a question to state that these radiations differ from each other in wavelength. While wave-optics enables us to understand why it is possible for well-defined images of external objects to be formed on the retinae of our eyes, the mechanism by which the incidence of the light on the retinae is communicated to the cerebral centres and its relation to the sensations which we perceive are subjects that stand completely outside the scope of the wave-theory of light. We have therefore of necessity to seek for an answer to our questions on the basis of the alternative approach provided by the quantum theory of radiation.

If a beam of monochromatic light falls upon a matt white surface, the illuminated object as seen by our eyes exhibits two distinct subjective features, viz., its brightness or luminosity and its hue or colour. From a physical point of view, the light falling on the surface has two distinct and definable properties, firstly, the radiant energy incident on it per unit of area per unit of time, and secondly, the magnitude of the quanta or units of light energy comprised in the beam. We are therefore led to associate the two characters of subjective perception respectively with the two physical attributes of the light, in other words, luminosity with energy-flux and colour with the magnitude of the individual light-quanta, and to infer that our eyes perceive colour by reason of the fact that light energy appears in discrete quanta and that these quanta are of different magnitude for the different rays in the spectrum. That we are justified in thus associating the sensation of colour with the magnitude of the light-quanta is reinforced by the consideration that for light to be perceived it must first be

absorbed by the visual receptor and such absorption necessarily occurs in complete quanta.

We have begun by considering the case of monochromatic light for the reason that it is the simplest case: monochromatic light does not admit of any further analysis. Only then it becomes possible to indicate the correlation between the physical properties of light and our sensory perceptions of the same in an unequivocal fashion. The sensations which result from the superposition of light of different colours or of different spectral composition present problems of greater complexity. They are no doubt of scientific interest and of practical importance, but we can scarcely hope that their study would lead us to an understanding of the fundamental aspects of the perception of light and colour. On the other hand, as is well known, they have led in the past to controversies and discussions of an unprofitable nature on various questions, of which it is sufficient to mention the two following as examples: Are there only three primary colours or a larger number? Which of the colours we perceive should be regarded as fundamental and which others as derived therefrom?

2. The duplicity of human vision

Our eyes are capable of functioning and serving as usefully over an enormous range of intensities. It has been estimated that the illumination of horizontal ground by the night-sky without moon is only about a hundred-millionth part of that received in direct sunlight, and yet it suffices for finding our way and keeping to the path provided our eyes are well adapted to darkness. That the mechanisms which function and enable us to perceive light are identical at both ends of this vast range of illumination is scarcely to be believed. Indeed, as is well known, the character of the sensations evoked is not the same in the two cases. In night-vision our eyes perceive differences in luminosity but their appreciation of colour is obviously imperfect. There are also other features which distinguish day-vision from night-vision, but we shall not pause here to discuss them.

In the year 1866, the retinologist Max Schultze announced a conclusion to which he had been led by an extended series of investigations in comparative ocular histology. He noted that the retinae of nocturnal vertebrates had many rods, and few cones or even none, while diurnal species had retinae with many cones which might even lack rods entirely. Thus, arose the idea that the cones are the receptors for daylight-vision and the rods for night-vision. That two types of vision exist and must be distinguished is very generally recognized, and they have indeed been given special names, viz., photopic and scotopic vision respectively. In the literature of the subject it is also generally assumed that photopic vision is mediated by the cones and scotopic vision by the rods in the retinae. But this assignment of the two types of vision to two sets of receptors in the retina does not really take us far. We have to ask ourselves whether the physical and

physiological processes are the same in the two types of vision or whether they are different and if so, in what respects.

In night-vision, our eyes have to serve us at the very lowest levels of illumination and a supersensitive receptor is clearly necessary for their successful functioning in such circumstances. On the other hand, in daylight-vision, the levels of illumination are higher; indeed, the quantity of light available in day-vision is, judging by the standards obtaining in night-vision, enormously larger than is adequate for its effective perception. Hence, a relatively insensitive receptor is what is actually needed. A further aspect of the matter that should be taken note of is that our eyes have to serve us both at very low and at very high levels of illumination, though, of course, not simultaneously. It would evidently be desirable that the supersensitive mechanism of night-vision is put out of action when the insensitive mechanism needed for daylight-vision is functioning; it would, of course, then be necessary that the apparatus of night-vision is restored and put back into action when it is actually needed. No such switching off and on is needed in the case of daylight-vision.

The foregoing remarks make it clear that the mechanisms of photopic and of scotopic vision would differ in certain respects. The exact nature of such difference is however best discussed at a later stage after the actual facts regarding the photopic and scotopic perception of light have been reviewed.

3. The facts of colour perception

From our present point of view, the most important facts concerning colour and daylight-vision are the relationships which exist between the subjectively perceived sensations of luminosity and colour and their physical counterparts, viz., the total energy-flux and the magnitude of the energy-quanta appearing in different parts of the visible spectrum. We may first briefly recall the distribution of colour in the spectrum. The colours observed in it differ so obviously from each other that common usage finds it convenient to give them different names to aid us in recalling them to our minds, viz., red, orange, yellow, green, blue and violet. The ranges over which these designations are applied vary with the individuals concerned, and only a kind of general average can therefore be regarded as possessing any significance. Expressed in wave-numbers and therefore directly related to the magnitude of the energy-quanta, these ranges are, respectively, red (13,000–16,000), orange (16,000–17,000), yellow (17,000–17,600), green (17,600–20,200), blue (20,200–23,000) and violet (23,000–26,000). It is noteworthy that while the ranges in wave-numbers covered by the designations red, green, blue and violet are all of the same order of magnitude, the colours designated as orange and yellow cover much smaller ranges.

We shall return presently to a more detailed discussion of the colour sequence observed in the spectrum, and proceed meanwhile to consider the relation

between the subjectively perceived brightness in different parts of the spectrum and the physically measurable energy-distribution in it. The essential features of this relationship can be established in a very simple manner by holding a diffraction grating in front of the eye and viewing the straight filament of a tungsten lamp, the current flowing through which is controlled by a rheostat. Observations of the first-order spectrum into which the luminous filament appears drawn out show that the distribution of luminosity in it is quite different from the energy-distribution in thermal black-body radiation as given by the Planck formula. According to the latter formula, the wavelength of maximum energy in the spectrum lies in the remote infra-red when the source has a temperature of 500°K ., and though it moves towards the red end of the visible spectrum as the temperature is raised, it remains outside the visible spectrum even at as high a temperature as $3,000^{\circ}\text{K}$. On the other hand, the maximum luminosity as visually observed appears well within the spectrum even when the temperature of the filament is so low that it glows only feebly with a red colour. As the temperature of the filament is raised and it becomes brilliantly incandescent, the point of maximum luminosity in the spectrum moves swiftly towards shorter wavelengths and finally reaches a point in the greenish-yellow region of the spectrum at about 5600 \AA beyond which it ceases to move any further. This is also the wavelength of maximum visual intensity in the spectrum of direct sunlight. In the spectrum of the light of the blue sky, in which the energy-distribution relative to sunlight is radically altered, the position of the maximum visual intensity is nevertheless not appreciably different. It is evident from these facts that it is a characteristic of daylight-vision that the eye has a highly pronounced maximum of visual sensitivity at about 5600 \AA on either side of which the visibility of radiation falls off rapidly. It is also evident from the observations that such falling off of visibility is less rapid towards the red end of the spectrum than towards the violet.

The features referred to above find quantitative expression in the “relative luminous efficiency” curves for monochromatic radiations appearing in the visible spectrum which have been determined by several investigators. The two methods most often used for this purpose are the so-called step-by-step method and the flicker method. In the former method, the difficulties of heterochromatic photometry are minimised by dividing up the spectrum into a fairly large number of strips (twenty or more) and successively comparing the intensities of adjoining strips. In the other method, the luminosity of monochromatic radiation is determined by the method of comparison at the rate of 10–20 times per second against a constant source of white light, the intensity of the monochromatic light being varied until the flicker experienced is a minimum. Differences are noticed between the determinations made by different observers, but by averaging the results obtained with a large number of observers, a luminous efficiency curve is obtained which can be regarded as a property of normal human vision. The results obtained by the two different methods are about the same, though some

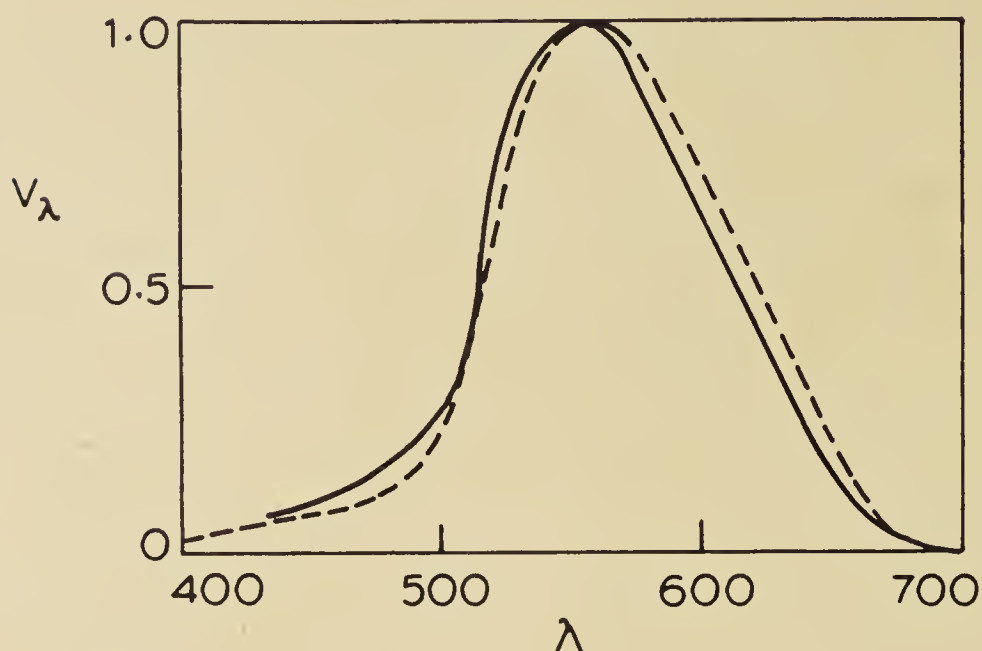


Figure 1. Relative luminous efficiency curves by the step-by-step method (—) and the flicker method (-----).

discrepancies are noticeable. This is shown by the two curves reproduced as figure 1 above exhibiting the results obtained by Gibson and Tyndall with the step-by-step method, and by Coblentz and Emerson with the flicker method.

We now return to the colours exhibited by monochromatic light. Earlier, it was indicated that the varying colours of the spectrum represent our subjective perception of the physical fact that the energy-quanta are different in its different regions. On this basis, we should expect the colours of the spectrum to form a continuous sequence, in other words that the spectrum can be divided into a great many parts or sections of which the colour can be perceived to be different. That is indeed actually the case. The number of distinct patches in the spectrum which when set side by side cannot be matched by any alteration in relative brightness has been estimated as about 250. If all the sections into which the spectrum may thus be divided were of equal width on a frequency scale, the smallest spectral shift giving rise to an observable change in colour would be about 50 wave-numbers. If this figure were accepted, it would mean that the human eye possesses a most remarkable degree of sensitivity to differences in colour and that it is capable of appreciating a difference less than one-half of 1%. In the magnitude of the light quantum received and absorbed by the retina as a difference in colour of the radiation.

It should be remarked, however, that the minimum spectral shift needed for a noticeable change of colour is not the same at all parts of the spectrum. It exhibits very significant variations, being in some parts smaller and in other parts larger than the figure stated above. Numerous investigations have been made in the past to determine the minimum in various parts of the spectrum and when the results reported are compared with each other, one finds a general agreement regarding certain features, viz., that in the region around 4900 Å and also in the region around 5900 Å, the minimum has quite small values, being respectively about 9

and 11 Å, and that in the intermediate region, viz., around 5400 Å, it is distinctly larger, being about 21 Å. Expressed in wave-numbers, these same figures are, respectively, 38 and 26 and 62 wave-numbers as against the averaged figures of 50 stated above. At wavelengths less than 4900 Å and greater than 5900 Å the determinations show that the minimum shift of wavelength increases rapidly. In these regions, however, the quantitative results of different investigators differ rather widely from each other.

The method by which the data of the kind referred are obtainable may be briefly described as follows: The observer views the two halves of a photometric field illuminated respectively by light from two adjacent regions in the spectrum of which the separation can be varied. The relative brightness of the two halves of the field is adjusted to equality by the use of a rotating sector disk or by some other device. If, when so matched, the two parts of the field appear definitely different, the spectral shift giving rise to the difference represents the least perceptible to the eye as a difference in colour. Figure 2 below exhibits “the hue

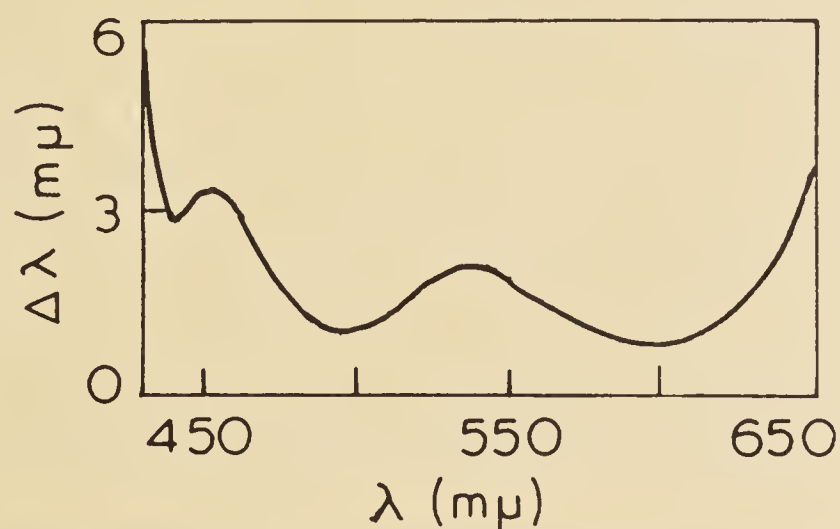


Figure 2. Hue discrimination curve in the spectrum, according to Wright and Pitt.

discrimination curve” in the spectrum obtained in this manner and reported by two observers. The abscissae in the curves are the wavelengths of monochromatic light in millimicrons, while the ordinates are the smallest shifts of wavelength (also in millimicrons) giving rise to an observable difference in colour. The figure exhibits the features already referred to above, and another not there mentioned, viz., the existence of a marked dip in the hue discrimination curve at about 4400 Å. Most of the published investigations report this feature and there is no doubt that it represents a well-established result.

Quite apart from the results of specific measurements made by the methods referred to above, it should be stated that a simple inspection of the spectrum by the unaided eye indicates that the colour sequence in the spectrum changes rapidly in certain regions, less rapidly in others and much less rapidly in certain others. An observer with normal colour vision will notice that the change of the blue to the green of the spectrum takes place within a relatively small range of

wavelengths between, say, 4900 and 5000 Å. Likewise, he will notice that the transition from the yellow to the orange of the spectrum takes place between, say, 5900 and 6000 Å. On the other hand, the transition from green to yellow is continuous, so much so that it is difficult to locate with any exactness the boundary between these two colours. The boundary between the blue and violet regions of the spectrum is placed in very different positions by different observers and indeed, it would seem that Newton was not altogether without justification when he put an additional colour "indigo" between blue and violet.

4. The mechanism of photopic vision

We now proceed to consider the significance of the facts regarding colour perception set forth above. For the reasons already explained, we associate the sensation of luminosity with the physical intensity or energy-flux, and the sensation of colour with the magnitude of the energy-quanta comprised in the radiation. Both the luminosity and colour of monochromatic radiation admit of study by appropriate physical methods which lead to quantitative results. These results do not contradict the physical interpretations proposed and they accordingly require to be further examined and explained. In other words, we have to answer various questions concerning them. In the first place, why does the luminous efficiency of monochromatic radiation vary in the manner observed and exhibit a maximum around 5600 Å? What is the factor which limits the power of the eye to discriminate differences in colour in the different parts of the spectrum? Why is it as great as it actually is in some parts, and why it is smaller in others?

The human eye has often been compared with a photographic camera. There are indeed some resemblances; in both cases we have a light-tight box covered inside with dark pigment to absorb unwanted light, a shutter to exclude light when desired and an adjustable diaphragm to regulate its admission when necessary. In both cases also, we have an optical system with front and rear components capable of adjustment so as to form a focussed image at the rear of the box. But to stress these structural similarities between a photographic camera and the human eye is liable to make us forget that the basic purposes which they are intended to serve are fundamentally dissimilar. A photographic camera serves to make a record of the light image on the sensitive film which can be developed and preserved. On the other hand, the retina of the eye serves both as a receiver and as a transmitter to the cerebrum of the energy of light falling on it. Whereas a photographic film can be used only once, the retina of the human eye is always ready for use. Indeed, vision would be useless to us if it did not carry with it the ability to view objects in different directions in quick succession one after another.

It is self-evident that light which merely passes through the retina and is absorbed by the pigmentary epithelium behind it would be ineffective in vision. In

other words, the absorption of light by pigments present within the retina itself is the first and necessary step for vision to be possible. But it is equally evident that unless such absorption goes hand in hand with a retransmission of the absorbed energy to the cerebral centres through the optic nerves, vision cannot result. It should also be remarked that since the colour perceived is determined by the magnitude of the energy-quanta comprised in the radiation, we have to assume that each quantum of energy absorbed is transferred immediately to the neurons without addition or subtraction. It would not be possible otherwise to explain the remarkable precision actually exhibited by our sense of colour discrimination. Merely as an example of such sensitivity, it may be mentioned that the two components of the sodium doublet whose wavelengths are 5890 and 5896 Å can be perceived to be of different colours in appropriate circumstances.

The facts of colour perception thus lead us to a quite simple and definite picture of the functioning of the retina in photopic or day-vision. We postulate that the light-sensitive receptors in the retina contain certain pigments which possess the power to transfer the light-energy absorbed by them to the neurons and return to their state of lowest energy. The known facts regarding the propagation of nervous disturbances and the production of electrical potentials by the infall of light on our eyes suggest that the energy transferred from the pigments assumes the form of an electrical disturbance in the receptors which is conducted through the optic nerves and on reaching the cerebral centres there excites the sensations we perceive. But we shall not pursue this aspect of the matter any further here.

5. The characters of scotopic vision

We now proceed to consider the actual facts regarding the perception of light at low levels of illumination, also referred to as scotopic vision. Earlier in this memoir it was suggested that the duplicity of human vision calls for a mechanism which could switch off the apparatus of scotopic vision when there is ample illumination and photopic vision can therefore function, and would switch it on again when the illumination is very feeble and photopic vision ceases to be possible. That such a mechanism is actually provided is evident from our own sensations when we move from sunshine into a dark chamber and *vice-versa*. The switching-on process is the slower of the two, since it is necessary to remain in the dark for at least 30 min for our eyes to develop the full sensitivity characteristic of scotopic vision. The switching-off process is somewhat quicker, but its duration is found to depend on the intensity of the light to which the retina is exposed.

Earlier, it was mentioned that in scotopic vision, the colour sense is imperfect. Such imperfection is due largely to the circumstance that the great sensitivity to light characteristic of scotopic vision does not extend to the parts of the spectrum which are both luminous and colourful, viz., the red and orange regions. Indeed, when any object of a scarlet-red colour is viewed in a darkened room, it appears

quite black. The characteristic features of scotopic vision are however best appreciated by studying the appearance of a continuous spectrum in scotopic conditions. A simple and convenient way of doing this is for the observer in a dark room to examine sky-light entering the room through a long vertical slit through a glass diffraction grating held in front of his eye. If the observations are made in day-time, the first-order diffraction spectrum of the slit then seen exhibits the familiar features characteristic of photopic vision. If, on the other hand, the observation is made at night when the sky is lit by moonlight (or in the absence of the moon by the lights of the city), the spectrum appears greatly shortened by the absence of all wavelengths greater than about 6000 \AA . By making the observations during the twilight hours (evening or morning), the progressive change from the photopic to the scotopic spectrum or *vice-versa* can be readily followed. The changeover can be hastened or slowed down by the simple method of narrowing or widening the slit through which sky-light enters the dark room, or by the observer moving away from or towards the slit. In either case, large changes in the visual intensity of the spectrum result and the entire series of changes from the photopic to the scotopic conditions can be quickly and conveniently followed. Indeed, one can go down to the stage in which the intensity of the spectrum approaches the threshold of vision.

A characteristic feature of the spectrum seen under scotopic conditions is that the wavelength of maximum visual intensity shifts towards the blue as compared with photopic vision. Quantitative determinations of the relative luminous efficiency curve at low levels of illumination have been made by several observers, the method used being that of direct photometric comparison against a white field of low luminosity. A typical set of results is shown graphically in figure 3. It will be seen that the relative luminous efficiency becomes negligible at wave-

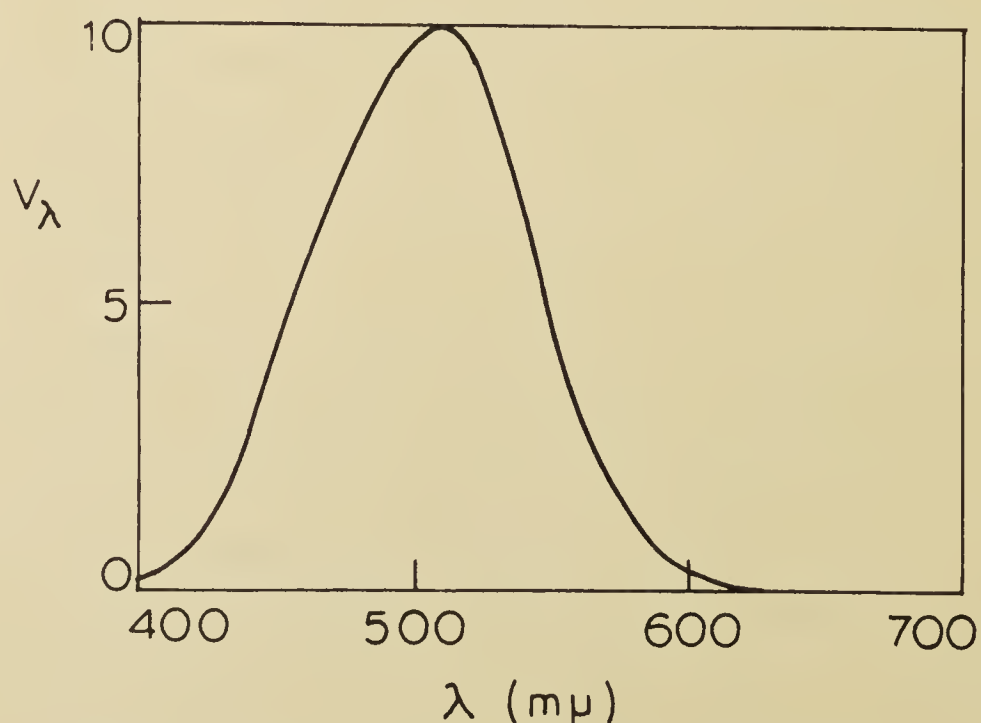


Figure 3. Relative luminous efficiency in scotopic vision.

lengths greater than about 6000 \AA , while its maximum appears at about 5100 \AA as against 5600 \AA in photopic vision.

A question of special interest is whether the spectrum seen under scotopic conditions exhibits the colour sequence seen in photopic vision (apart from the disappearance of the longer wavelengths) or whether the scotopic spectrum is achromatic as is often stated. Observations made by the methods described above gave a clear answer to the issue here raised. Scotopic vision covers a wide range of intensities differing at its two ends by a large factor; whether in any particular case, we are observing the spectrum under scotopic conditions is indicated by the relative luminosity of the regions around 5000 \AA and 6000 \AA , the latter being negligible in scotopic conditions, while in photopic conditions, the latter is much more intense than the former. While the scotopic spectrum exhibits no visible colour anywhere at the lowest levels of intensity, this ceases to be the case at greater intensities. A greenish tinge becomes visible around the region of maximum luminosity; this is more obvious at greater intensities, and the differences in colour between the centre of the spectrum and its two ends are also then perceptible. As we approach the upper limits of scotopic vision, the colours observed become more vivid, but remain distinctly weaker and less saturated than in photopic vision.

6. The mechanism of scotopic vision

In their fundamental aspects, scotopic and photopic vision resemble each other closely. It is just as easy to view different objects one after another in quick succession at low levels of illumination as at higher levels and indeed one is then less troubled by after-images, glare and other disturbances. Visual photometry is possible in scotopic as in photopic vision and indeed in some respects easier, as for instance in heterochromatic photometry. If scotopic vision had been entirely achromatic at all levels of illumination, this feature would differentiate it fundamentally from photopic vision. But, as we have seen, such is not the case. The colour sense is actually present at the higher levels of illumination falling within the scotopic range and the colours then perceived, though less vivid, do not otherwise differ from those seen in photopic conditions.

In view of what has been stated, one would be justified in assuming that in their basic aspects, the mechanisms of scotopic and photopic vision are similar, in other words that in either case, the retinal pigments function by a simple transference of the light energy absorbed by them to the receptors, followed by a return to their normal energy state. The differences between the characters of photopic and scotopic vision described earlier do not appear to be inconsistent with such an assumption. That the relative luminous efficiency curve for scotopic vision differs from that determined for photopic vision is readily understood on the basis that the retinal pigments which function in the two cases are different.

That scotopic vision goes down to lower levels of illumination also becomes intelligible on the basis that the retinal pigment which functions is present in substantial quantities and can therefore trap a larger proportion of the incident energy quanta and pass it on to the receptors.

It now remains to explain how the switching-off and switching-on of scotopic vision take place respectively when the observer moves from low levels of illumination to high levels and *vice-versa*. It may justifiably be inferred from the actual facts of observation that when the observer has been long enough in bright light, the pigment which mediates scotopic vision has been transformed by the incidence of such light on his retina into a different substance which cannot so function; *vice-versa*, when the observer remains in darkness long enough, the pigment is regenerated in some fashion. The switch-off would proceed at a rate proportional to the intensity of light to which the retina is exposed and would be the quicker, the more intense such illumination is. The regeneration of the pigment, on the other hand, would occur in the absence of light or at very low levels of illumination and its rate would be determined by purely chemical or biochemical factors. The destruction of the pigment by bright light and its regeneration in the dark here contemplated are merely auxiliary processes which make it possible for human vision to function efficiently both at high and at low levels of illumination. There is no need and indeed no justification for assuming that they form an essential part of the actual mechanism of scotopic vision. Neither would photopic vision demand the destruction and regeneration of the visual pigments which function in it as an essential part of the visual mechanism.

The perception of light and colour and the physiology of vision—Part II. The visual pigments

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1. Introduction

In the first part of this memoir, the view has been put forward that our perception of light and colour is made possible by the presence in the retina of certain pigments which possess the power to absorb light and to transfer the energy thus absorbed immediately to the sensory receptors, thereby enabling us to perceive the absorbed energy as light. The identification of the visual pigments which perform these functions, in other words the determination of their chemical nature and a knowledge of their spectroscopic behaviour and distribution in the retina are the foundations on which any explanation of the facts of experience regarding vision must rest. We shall address ourselves in this part of the memoir to the problem which thus confronts us.

2. Viewing the retina in action

Any observer endowed with normal colour vision can perform the experiments now to be described. These do not require elaborate equipment and enable him to see his own retina in the act of functioning and observe its response to light in different parts of spectrum. From the results of the experiments, it is possible to infer the number and the distribution in the retina as well as the spectroscopic behaviour of the visual pigments which enable us to perceive light and colour.

The technique of the observations is quite simple. The observer sits facing a brightly illuminated white screen at a convenient distance from it and views the screen through a colour filter, either monocularly or binocularly as he may find best suits him. After allowing a sufficient time for the vision to adapt itself to the effects of the colour filter, the observer fixes his vision on some particular point on the screen and suddenly removes the filter. He will then recognize on the screen a highly enlarged projection of the macular region of his own retina, including especially the fovea centralis and the foveola at its midpoint. The details of the

picture seen and the colours it exhibits depend very much on the filter employed. The picture soon fades away but it can be restored by putting back the filter and removing it again at short intervals of time. The picture can then be examined more closely.

The appearance of an image of the observer's own retina on the screen can be explained in general terms in the following manner. The colour filter employed cuts out or enfeebles certain parts of the spectrum while transmitting the other parts of it freely. As a consequence of the removal of the filter, the spectral components which are cut out or enfeebled by it are restored and suddenly illuminate the retina. Localised sensations are then excited, determined by the luminous efficiency of these spectral components and by the response to them of the receptors located in each element of area of the retina. The sensations thus excited manifest themselves to the sensory mechanism of the eye as an image of the retina which appears projected on the screen, each element of area exhibiting its own response to the illumination suddenly falling on it.

Before we proceed to describe and comment on the results observed with individual filters, it may be useful to mention a few particulars requiring attention in the experiments. It is necessary that the illumination of the screen should be adequate and that it should be as nearly uniform as possible. The observations should therefore be made by daylight, the screen being placed facing the windows in a well-lighted room and the observer should sit facing the screen and with his back to the windows. A projection screen of the well-known kind which is plastered over with tiny glass spheres is very suitable. A medium-sized screen, say 170 cm by 125 cm, is adequate and a convenient distance from the observer to a screen of that size is 350 cm. It is possible to use colour filters of different kinds, as for example glass cells of sufficient size containing absorbing solutions or plates of coloured glass. However, for the studies now under consideration, the most convenient filters are those which can be prepared by staining gelatine films on glass (of the kind used in photography) with a water-soluble dye. By regulating the strength of the solution in which the plates are dipped and the period of immersion before they are taken out and allowed to dry, the depth of the staining can be controlled over a wide range. The filters should be held close to the eye so as to exclude all light except that passing through it.

3. Description of the effects observed

Quite spectacular effects are observed when the filter employed is a gelatine film on glass stained lightly with methyl-violet. The filter appears a purplish-blue by transmitted light. Holding it before the eye for a few seconds and then removing it, the observer sees on the screen an enormously magnified image of his own fovea as a disk of light which is green in colour, and at the centre of it a bright spot of the same hue which is the pit or depression in the fovea known as the

foveola. If the filter is held for a somewhat longer time before it is removed, the fovea is much brighter and then appears surrounded by a halo of golden-yellow hue some five or six times larger in diameter but less luminous than the fovea itself. The fovea with the foveola at its centre appears at the point on the screen at which the observer has fixed his vision before removing the filter. If he shifts his gaze, they also move, thereby showing clearly that what is seen on the screen is a projected image of the observer's own retina. (See plate 1, figure 1.)

Spectroscopic examination shows that the filter lightly stained by methyl-violet has a strong absorption band in the orange, a weaker one in the green, and a very weak absorption in the region between them. When more heavily stained, the absorption becomes complete in all these regions and extends further into the green. A film stained heavily so that it cuts out the green completely but transmits the red and the blue of the spectrum appears of a deep purple colour. The use of such a heavily stained filter is however of no particular advantage, and on the other hand makes the phenomena rather less spectacular.

A noteworthy fact that emerges from the studies is that a filter whose absorption spectrum appears *exclusively* in the green part of the spectrum, in other words between 4900 and 5600 Å, does *not* give any observable effects of the kind referred to above. Several colour filters of this kind are available, amongst which may be mentioned very dilute solutions of potassium permanganate in water, or of iodine in carbon tetrachloride. More convenient, however, are gelatine films stained lightly by a suitable dye as, for example, rhodamine or eosine, so as to enfeeble or cut out the green region without affecting the rest of the spectrum. Holding such a filter in front of the eye for a little while and then removing it, the screen presents the same appearance as before the filter is interposed. Prolonging the period for which the filter is held before the eye prior to its removal makes no noticeable difference.

Though, as stated above, colour filters that absorb only the green part of the spectrum do not give rise to the effects under consideration, it is clear from the example of the methyl-violet filter that absorption in the green region can co-operate with absorption in adjoining regions of greater wavelengths and enable them to be observed. We may therefore conveniently divide the spectrum into three regions which we may denote as A, B and C and classify the filters and the effects they produce by reference to the regions of the spectrum in which their absorption appears. The violet-blue region of the spectrum is denoted by A, and green by B, and the yellow, orange and red may be grouped together and referred to as C.

As an illustration of the usefulness of the classification proposed in relation to the effects observed, we may here mention two cases in which very beautiful effects are observed but of a different nature. The colour filters in both cases are aqueous solutions contained in glass cells of equal thickness, 5 cm in each case. One solution is that of nickel chloride and the other of the dye-stuff lissamine-green sufficiently diluted so as to transmit plenty of light. The nickel chloride

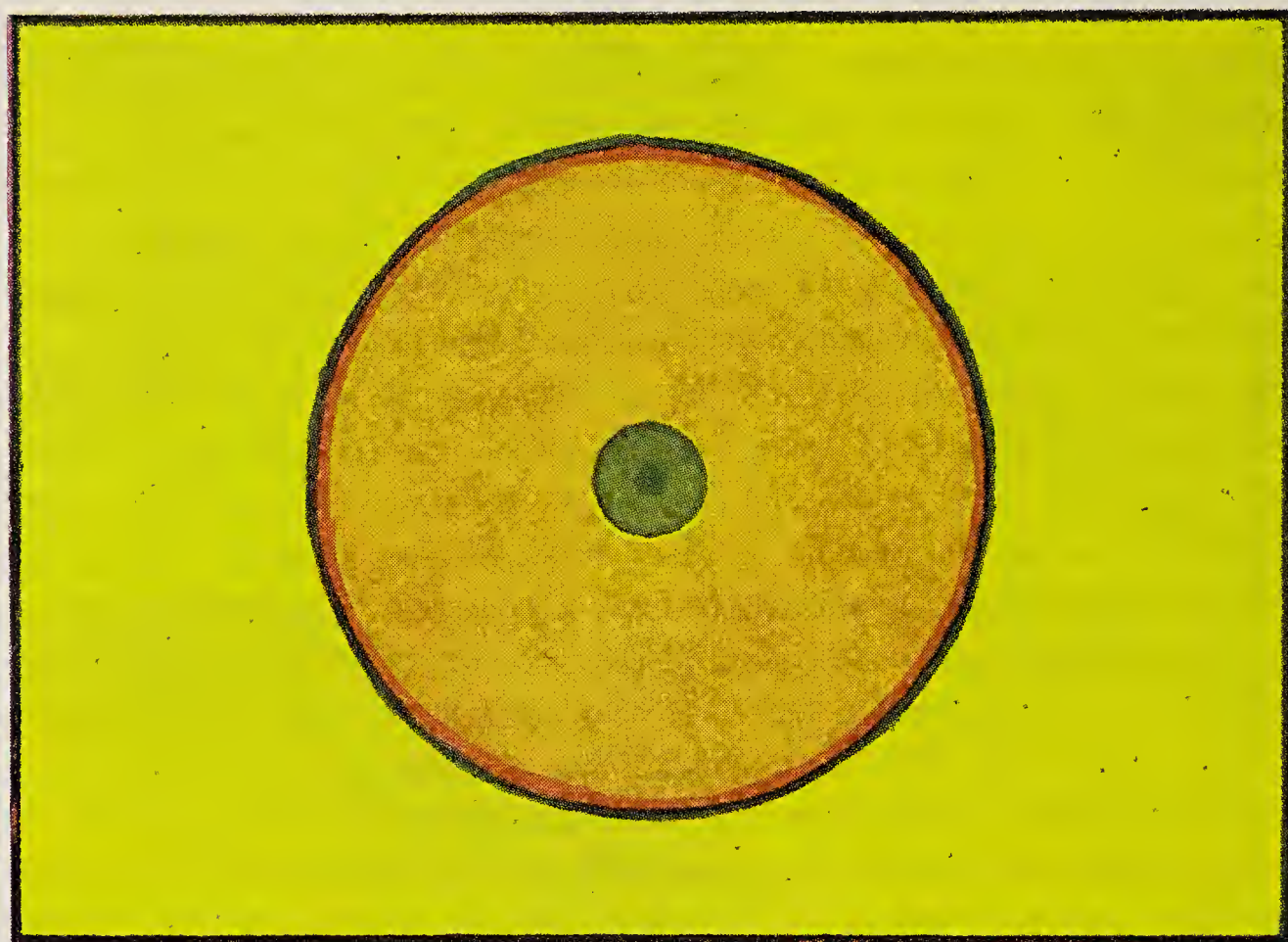


Figure 1. Methyl violet filter.

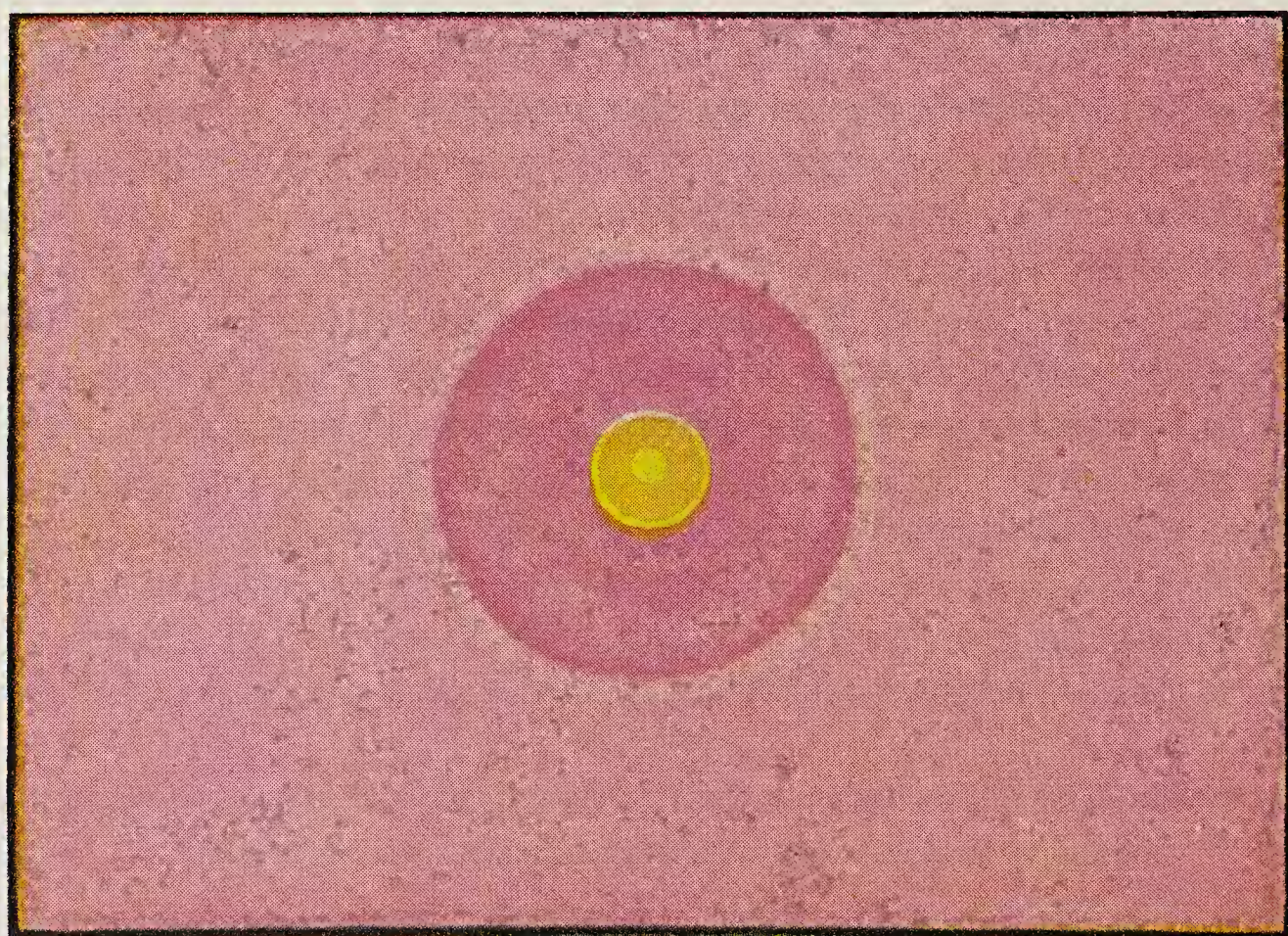


Figure 2. Lissamine green filter.

Plate 1. Pictures of retina seen by the filter technique.

solution is completely transparent in the green, and examination by a pocket spectroscope shows that it also allows the adjoining part of the blue to pass through, but cuts out the red, orange and yellow more or less completely. It thus belongs to the class of filter which we denote as AC. The solution of lissamine-green appears blue-green by transmitted light and while resembling the nickel chloride in allowing part of the blue to come through, it cuts out the red, orange and yellow completely and also part of the green. It thus belongs to the class ABC.

Holding the nickel chloride solution before the eye for a few seconds and then removing it, a brilliant rose-red glow is seen to cover the entire screen; at the centre of the field and as a very inconspicuous feature appears a small circular area which appears of a different hue and brightness from the rest of the field. On the other hand, when the lissamine-green solution is used for the observations, a highly magnified image of the fovea, bright yellow in colour and more luminous than the rest of the field, and the foveola at its centre are the most conspicuous features which the observer sees on the screen. A reddish glow covers the entire screen, but around the foveal image appears a halo of indefinite hue. (See plate 1, figure 2).

The filters of the species designated as A and as AB transmit the red, orange and yellow regions of the spectrum perfectly but cut off the shorter wavelengths to varying extents. As their cut-off in the spectrum moves from the extreme violet into the green and then further, the colour of the transmitted light progressively alters from the palest yellow to the deepest orange. All filters of the kind mentioned exhibit effects having certain features in common, though differing in detail. For example, using a filter of pale yellow hue having a cut-off at 4500 \AA , its sudden removal from before the eye after an adequate interval results in the appearance of a violet-tinted glow which covers the entire screen. Neither the fovea nor the foveola nor any halo surrounding them can be seen. But at the centre of the field in the direct line of the observer's vision, there is a hint of the glow being somewhat dimmer than elsewhere on the screen. With another filter of a deep yellow colour which has a cut-off at 5100 \AA , similar effects are noticed, but the glow which appears covering the screen is blue in colour and much brighter than that observed with the pale yellow filter. Orange filters give effects which are similar to those seen with the deep yellow filter but are not by any means more conspicuous; on the other hand, the effects are rather less conspicuous since the glow does not display any vivid colour and also ceases more quickly to be observable. Thus, an extension of the region of absorption by the filter from section A of the spectrum into section B does not make any real difference to the results, apart from making them less easy of observation.

Gelatine filters of the classes C and AC may be prepared by staining them *very lightly* with the dyes methylene-blue and lissamine-green respectively. Holding such filters before the eye and then removing them, the entire area of the screen exhibits a glow of a colour which differs for the two species of the filter, orange in one case, and rose-red in the other. But no image of the fovea or foveola appears on the screen. Only filters of the classes BC and ABC exhibit the later

phenomenon. They may be prepared in great variety by staining gelatine films to any desired depth by blue or green, dyes (methylene blue and lissamine-green for example). Most blue glasses belong to the class BC and most green glasses to the class ABC. A photographic filter exhibiting a delicate green colour was however found to belong to the class AC. It cuts out the violet rays in the spectrum and visibly enfeebles the red, but has no noticeable absorption in any other part of the spectrum. Holding it before the eye and then removing it, the observer sees a beautiful purple glow covering the entire screen, while an inconspicuous feature appears at the centre of the field of vision in the shape of a small circular area where the glow is feebler than elsewhere.

Observations have been made with numerous filters of the classes BC and ABC. With every one of them, the foveal disk and the foveola at the centre are conspicuous features. It is also possible in many cases to observe a coloured halo five or six times larger in diameter than the foveal disk but of much lower intensity superposed on the general field of illumination on the screen following the removal of the filter.

4. The three visual pigments

We now proceed to consider the significance of the facts of observation reported above. We have seen that the entire spectrum may be divided into three sections which we have denoted as A, B and C respectively, and that the colour filters whose absorption appears exclusively in one or another of these three behave quite differently. It is a reasonable interpretation of the facts that the retina contains three pigments which are effective as absorbers of light and mediators of vision respectively in these three sections. We shall refer to them hereafter as pigments A, B and C respectively. Pigment A functions in the blue-violet region of the spectrum, pigment B in the green and pigment C in the orange, red and yellow. The facts of observation described earlier, however, compel us to qualify this statement and to recognize that the absorption spectrum of pigment C overlaps that of pigment B in the green to an appreciable extent. It is also necessary to assume that when the incident light causes pigment C to function, this results in the simultaneous functioning of pigment B in the same region of the retina, provided the wavelength of the incident light is within the region of overlap of the absorption spectra of the two pigments.

The effects observed on the viewing screen following the removal of the filter enable us to draw some useful inferences regarding the distribution in the retina of the visual pigments which give rise to them. The position is clearest with regard to pigment A which is the mediator of vision in the blue-violet region of the spectrum. The blue or violet glow covering the entire area of the screen seen with filters of class A clearly indicates that the visual pigment of that class is distributed over an extent of the retina many times larger in area than the fovea itself.

The appearance on the viewing screen of a highly enlarged and luminous image of the fovea and of the halo encircling it clearly demands the co-operation of the two pigments B and C, since these effects are only noticed when filters of the classes BC and ABC are employed. The colours displayed by the fovea and the halo in various cases also point to the same conclusion. We are thus led to infer that pigment B is present in its maximum density in the region of the fovea and has a considerable though smaller density in an area surrounding the fovea and having five or six times its diameter. The observations further indicate that pigment C is present in association with pigment B in the areas referred to and that it is also to be found distributed over the area of the macula well beyond the region in which the coloured haloes surrounding the fovea are observed.

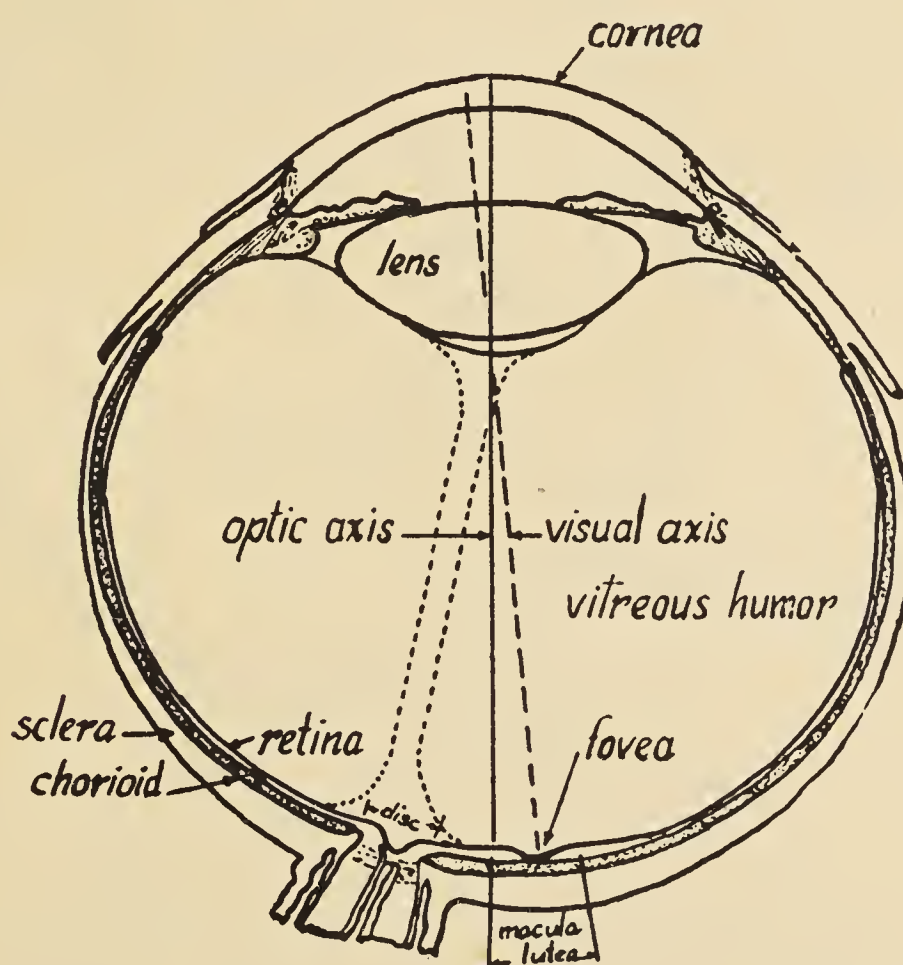


Figure 1. Horizontal section of the right human eye.

We may reasonably look for some evidence in support of the foregoing findings in the appearance of the retina as seen in the ophthalmoscope. The fundus of the human eye is visible in that instrument by reason of the diffusion of the light incident on the retina by the retina itself and by the materials behind it. The opinion expressed in the ophthalmological treatises (and copied therefrom into other books) is that the appearance of the retina is due to the diffusion of light by the choroid coat which lies behind the retina. Between the retina and the choroid coat, however, lies the pigment epithelium, the function of which is to absorb unwanted light traversing it in either direction. The efficiency of the pigment epithelium as an absorbing screen has therefore a very great influence on the

nature of the picture seen in the ophthalmoscope. This is indeed evident on a comparison between the appearance of the retina in the four cases of albinotic individuals, persons of fair complexion, and persons of dark and very dark complexions respectively. The blood-vessels in the choroid are clearly seen through the retinae of albinotic individuals. They are not seen in the other cases, what is actually visible being the surface of the retina upon which can be distinguished the optic disk, the retinal blood-vessels and the macula. The hue exhibited by the retinal surface is orange-red in persons of fair complexion, while in the case of negroes it is brick-red.

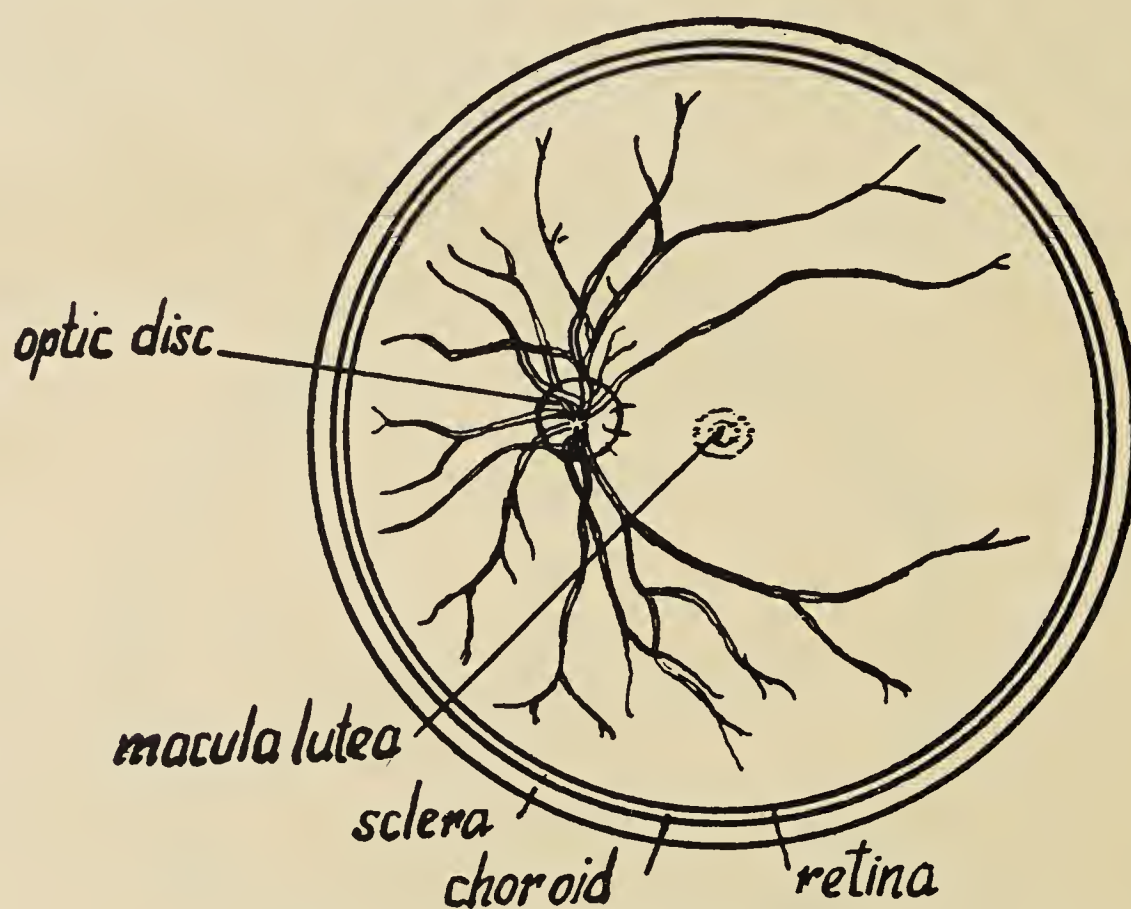


Figure 2. Fundus of the human eye.

What we are here specially interested in is the macular region which is physiologically the most important part of the fundus. This region is devoid of any visible blood-vessels, though it is encompassed on all sides by the twigs reaching down to it from the retinal blood-supply system. A specially significant fact is that in all cases, the macular region is of a distinctly darker tint than the rest of the fundus. Further, the fovea itself exhibits a blood-red hue in all cases. These are conspicuous features in the coloured illustrations of the fundus appearing in the ophthalmological treatises. The presence of pigments which between them cover the entire spectrum would explain the deeper colouring of the macular region. The presence in and around the fovea of a pigment which exercises a powerful absorption in the green region of the spectrum would account for that area exhibiting a blood-red hue. Thus, what is actually seen of the fundus through the ophthalmoscope does not contradict the conclusions reached through the present studies, but on the other hand gives them the clearest possible support.



Figure 3. Blood-vessels in the retina.



Figure 4. Perifoveal capillaries in the retina.

A further remark may be made here. Ophthalmologists not infrequently in their examination of the fundus make use of light from which the red rays have been excluded by a suitable filter. It is stated that the background of the retina then appears of a yellowish-green colour, the macula standing out as a lemon-yellow area, and that the blood-vessels running through the retina appear almost black with sharply defined outlines. That the macula is distinguishable by its colour from the rest of the retina in these circumstances has been explained as due to presence in it of appreciable quantities of the yellow pigment which gives to the macular region its anatomical name of *macula lutea*. This yellow pigment may reasonably be identified with our pigment A, the absorption of which appears exclusively in the blue-violet region of the spectrum.

5. Identification of the visual pigments

We now proceed to consider the problem of determining the chemical nature of the pigments present in the retina which are the mediators of photopic vision. We have designated them above as (A), (B) and (C) and formed a general idea of the spectral ranges within which they are operative. They should be capable of existing in association with the materials which form the living substance of the retina. Their absorption spectra should appear in the regions indicated and it is necessary that when they absorb light radiations, they should also be capable of passing on the energy thus absorbed immediately to the receptors in the retina. Finally also, since we are concerned with photopic vision and therefore with high levels of illumination, it is necessary that the pigments should possess in a reasonable measure the power to resist disruption or decomposition by the action of light.

The advances in organic chemistry made of recent years have resulted in the elucidation of the structure of numerous naturally occurring colouring matters and created a great body of knowledge connecting chemical constitution with optical behaviour. A well-established result which emerges from these researches is the relation between the manifestation of colour by a substance and the presence in its molecules of unbroken chains of alternate single and double bonds. It is found that the longer the chain of such bonds is, the further into the region of the visible does the absorption spectrum of the substance extend. Many naturally occurring pigments also fall into two classes, one in which the chain of alternate single and double bonds is an extended straight line, and the other in which it forms a closed ring within the molecule. The group of substances known as the carotenoids belong to the first class, while in the second class we find various substances playing highly important biological roles, including especially heme and chlorophyll. It is interesting and significant that the green leaves of growing plants contain colouring matters belonging to both of the classes referred to. Two

of them, viz., β -carotene and xanthophyll belong to the first class and two others, viz., chlorophyll-*a* and chlorophyll-*b* to the second.

As is well-known, the pigments present in green leaves form the pathway by which organised nature finds access to solar energy. They enable the energy of solar radiation to be utilized for the synthesis from carbon dioxide and water of carbohydrates and other constituents of living matter. The mechanism of this process—known as the photosynthesis by plants—has been the topic of numerous investigations. It is recognized that chlorophyll with the strong absorption of light which it exhibits at the extreme red end of the spectrum plays a leading role in photosynthesis and the view formerly prevailed that the other pigments present did not participate in the process. More recent studies indicate that the latter conclusion needs modification and that the carotenoid pigments also do play a part in photosynthesis. Cogent evidence is also forthcoming that the pigments in green leaves, including especially chlorophyll, act as energy-receiving and transferring agents and thus enable photosynthesis to take place. Whether they actually participate in the chemical changes which result in the formation of new compounds and if so in what manner are questions which at the present time remain in the speculative stage.

It would seem, therefore, that the pigments in green leaves and the pigments in our retinae play somewhat similar roles in their respective fields of activity. Hence, there are good grounds for assuming that the pigments concerned are either the same or else are very similar. Four pigments are needed for vision, three for photopic and one for scotopic vision. Two of them may well be carotenoids, one for each type of vision. There is no reason, however, for assuming that all four pigments are carotenoids. On the other hand, it is most improbable that this would be the case. Pigment B plays a role in human vision of special importance as it covers the part of the spectrum having the highest luminous efficiency. One would naturally expect that such a pigment would be a product of biological activity in the human organism and not a substance carried into the body through the medium of food products. Further, it is difficult to believe that any carotenoid would possess all the properties needed for pigment B, viz., an absorption spectrum lying in the region between 5000 and 6000 Å, a high efficiency as an energy-receiving and transferring agent and the chemical stability needed to resist disruption or decomposition under intense illumination. We are thus led to infer that pigment B belongs to the class of organic compounds which derive their colour from the presence in their molecular structure of a ring of alternating single and double bonds. That pigment C also belongs to that class is *prima facie* very probable.

Chlorophyll-*a* and chlorophyll-*b* are pyrrole pigments which are chemically very similar to each other. They owe their colour to a combination of four pyrrole nuclei joined together in a complex molecule, a special feature of importance being that a magnesium atom appears linked to the nitrogen atoms of the four pyrrole groups in the molecule. When the magnesium atom is removed by the

action of acids, the solution turns brownish and ceases to exhibit the colour characteristic of chlorophyll, thus demonstrating the importance of the metallic atom in relation to its spectroscopic behaviour. When we seek for a pigment which could perform in the retina a role analogous to that performed by chlorophyll-*a* in the green leaf, the obvious and indeed the only choice is the metallo-porphyrin compound known as ferroheme (or simply as heme). This is also a pyrrole pigment, being a compound of iron in the divalent state with one of the porphyrin group of compounds. The porphyrins contain a closed ring of eighteen bonds which are alternately single and double in their structure, and the iron atom occupies in heme a position in relation to the four nitrogens in the molecule which is the same as that of the magnesium atom in the chlorophyll structure. There is thus good reason for assuming that heme possesses the properties needed to enable it to function very efficiently as a visual pigment in the retina.

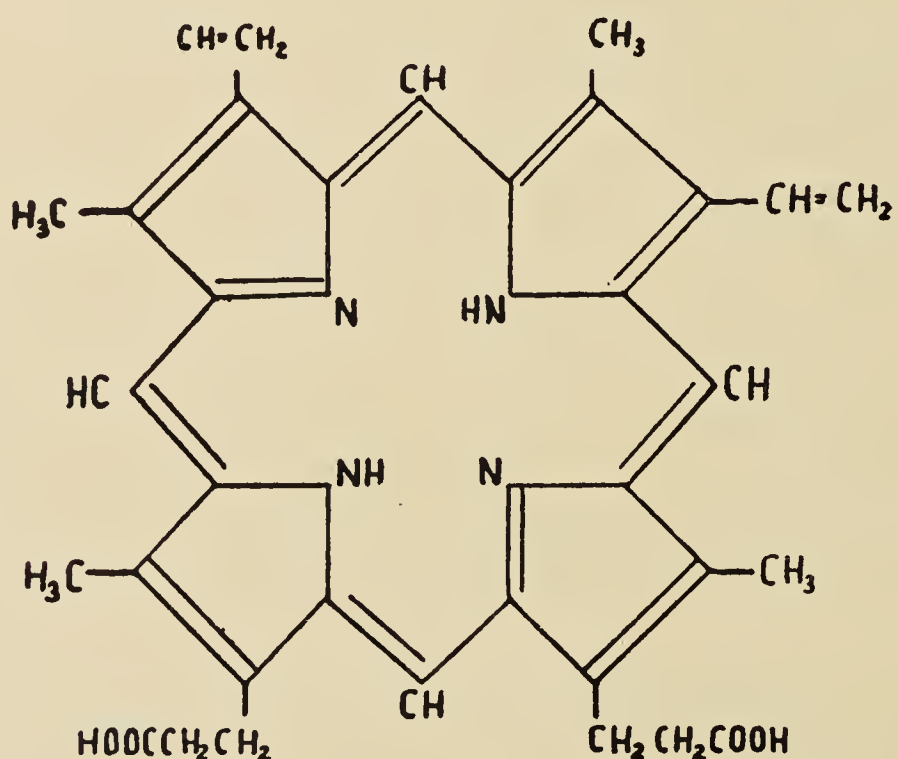


Figure 5. Molecular structure of protoporphyrin.

It is appropriate here to mention that heme in combination with different proteins plays a role of outstanding importance in the life of both plants and animals. The compound of heme with globin known as hemoglobin is present in the red-blood cells of vertebrates and by its ability to combine reversibly with oxygen without undergoing oxidation performs the unique and indispensable role of a carrier for the storage and transport of oxygen in the organism. Another heme-protein known as myoglobin is the respiratory pigment occurring in muscle cells of both vertebrates and invertebrates. The cytochromes are the most widely distributed of all the heme proteins and occur in the cells of nearly all aerobic organisms, both plant and animal. Catalase and the peroxidases are other

heme proteins which function as enzymes. This brief statement indicates the ubiquitous nature and extraordinary versatility of the heme proteins in performing biological roles of importance.

We shall later discuss the spectroscopic behaviour of heme in detail. It will suffice here to mention that all the heme proteins exhibit an intense absorption of light in the green region of the spectrum. Hemoglobin, for example, exhibits even in very dilute solutions a powerful absorption in the region of wavelengths between 5000 and 6000 Å, its maximum appearing around 5550 Å. That this absorption is a characteristic property of the porphyrin groups of compounds when a divalent metal atom occupies the central position in the molecule is shown by the fact that a powerful absorption with its maximum located at or near the same wavelength is also exhibited by several different porphyrins in combination with diverse metallic atoms which are divalent.

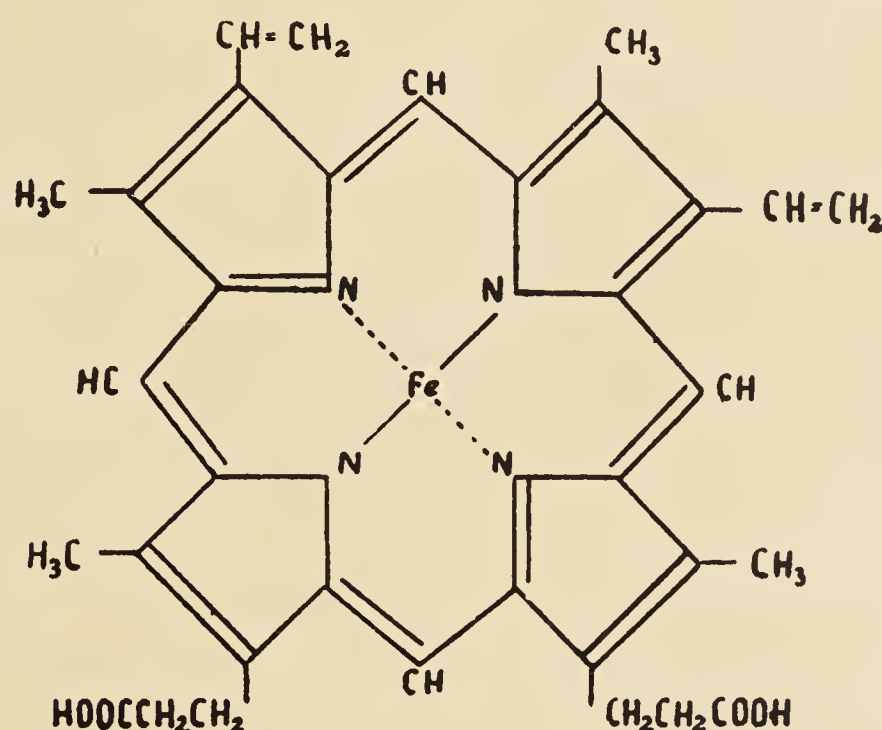


Figure 6. The molecular structure of heme.

The considerations set forth above accordingly lead us to identify ferroheme as our pigment B. We thereby add to the list of the many biological functions performed by ferroheme that of being the principal mediator of vision in the photopic range. Indeed, the absorption of light by ferroheme is so strong that no great quantity of this pigment would be needed in the retina to enable it to function effectively as the mediator of vision. That it is indeed the principal visual pigment finds strong support in the fact that the position of its absorption maximum is not very different from the wavelength of maximum visual sensitivity in the spectrum. The generally accepted value for the latter is 5550 Å, but it may actually be a little greater for persons with normal colour vision.

That the pigment A which functions in the region of wavelengths between 4000 and 5000 Å is a carotenoid is indicated by the fact that the absorption spectra of

carotenoids appear just in that region. As already mentioned earlier, the two carotenoids that are invariably found in the green leaves of growing plants are β -carotene and xanthophyll. These colouring matters are also present in the plasma of human blood and in human milk in varying amounts, evidently as the result of the consumption of articles of food containing them. There is however a noteworthy difference between the two pigments, viz., β -carotene is a precursor of vitamin-A, whereas xanthophyll is not. In other words, xanthophyll does not undergo fission and become transformed to vitamin-A in the human body. We may, therefore, with confidence assume that it is xanthophyll, and not β -carotene which is the pigment that finds its way into the human retina to function as a receptor in photopic vision.

The identification of pigment C has next to be considered. We have already noticed that while the absorption spectrum of this pigment appears principally in the yellow, orange and red regions of the spectrum, it also overlaps to some extent the region in which pigment B is operative, namely, the green of the spectrum. The reasons which make it probable that pigment C belongs to the same group of pyrrole compounds as pigment B have already been indicated. That the two pigments co-operate with other in producing the luminous effects described earlier on these pages is also significant. We are thus led to recognize that pigment C is closely related to pigment B. The suggestion that it is only an oxidised form of that pigment, in other words that it is ferriheme naturally presents itself. The spectroscopic and other evidence which supports and confirms this identification will be presented in a subsequent part of the present memoir.

The perception of light and colour and the physiology of vision—Part III. The carotenoid pigment

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1. Introduction

In the first part of this memoir, the facts of observation regarding the luminosity and colour perceived at different points in the spectrum were set out in detail. The mechanism of perception and the role played by the visual pigments in the retina which would account for the facts were then discussed. In the second part of the memoir, the number of visual pigments which function and the spectral regions in which they are effective were deduced from certain luminous effects which were described, and the considerations which enable these visual pigments to be identified were also set out.

We shall now proceed a step further and show how it is possible to connect the observed variations of luminosity and colour in the spectrum with the absorption characteristics of the visual pigments which enable us to perceive light and colour. We shall in the first instance consider the blue-violet region of the spectrum which exhibits several features of interest, including especially the fact that in that region—and no other—the unaided eye is capable of recognizing polarised light and even of determining its plane of vibration by sight. It will be shown that these and other features are explicable in terms of the structure, spectroscopic behaviour and disposition in the retina of the molecules of the carotenoid pigment xanthophyll which was identified in the second part of the memoir as the mediator of photopic vision in that part of the spectrum.

2. The carotenoid pigments

The carotenoids are so named by reason of their chemical relationship to carotene which is a plant pigment first isolated in crystal form from the roots of the cultivated carrot. They are a numerous family of compounds and are essentially plant products. Indeed, there is no evidence which would suggest that any carotenoid is produced *de novo* within the body of an animal. They enter the

body by way of the articles of food which are consumed by the animal and if assimilated, pass into the blood stream to be utilised or stored up where needed. The potential vitamin-A activity is an important function of some of them, including especially β -carotene. This is however not one of the potential uses of xanthophyll since it is not a precursor of vitamin-A. Accordingly, xanthophyll is either accumulated in certain organs or else is passed out of the body.

An interesting example of the storage of xanthophyll is furnished by the yolk of the domestic hen's egg which, as is well known, exhibits a bright yellow colour. It is a convenient source-material from which xanthophyll can be obtained for the study of its spectroscopic behaviour. Repeated treatment with warm acetone results in the extraction of the pigment and on filtration, a clear liquid exhibiting a golden-yellow colour is obtained. This contains xanthophyll and also its isomer zeaxanthin as a minor constituent. As the latter has a very similar spectroscopic behaviour, its presence is not inconvenient for the purpose in view.

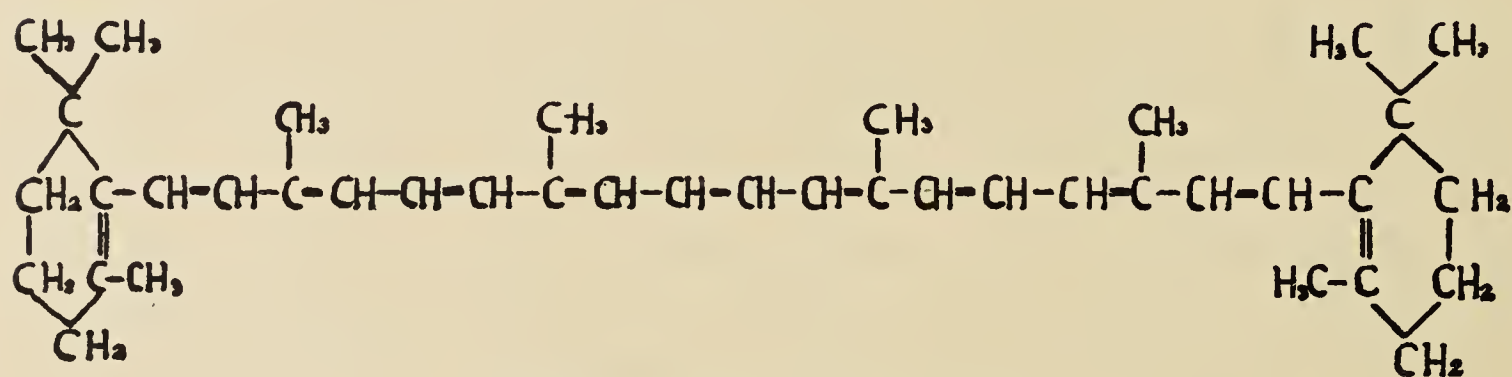


Figure 1. Structure of β -carotene.

Carotene is a hydrocarbon having the chemical formula $C_{40}H_{56}$ which appears in different isomeric forms, the most important of them being β -carotene which has the structure shown in figure 1. It will be seen that the two end-groups in the molecule have an identical structure and are joined together by a long chain in which single and double bonds alternate. It is this system of conjugated double bonds that is responsible for the absorption of light by the substance which extends into the visible region of the spectrum. The characteristics of the absorption spectrum of β -carotene in hexane solution are exhibited in the spectrophotometer curve reproduced as figure 2. It will be seen that it is negligible at wavelengths greater than 5200 \AA and that it rises very steeply in the region of wavelengths smaller than 5000 \AA . After passing through a succession of maxima, it drops down but much less rapidly to quite small values at the violet end of the spectrum. The absorption maxima are located at 4770 , 4500 and 4250 \AA , the last being visible only as a point of inflexion on the curve.

Xanthophyll (also referred to in the chemical literature as lutein) has the formula $C_{40}H_{56}O_2$ and its structure which is shown in figure 3 exhibits its chemical nature as dihydroxy- α -carotene. The two end-groups in xanthophyll differ in their structure and this difference reflects the difference between α -carotene and β -carotene; the latter is symmetrical whereas the former is not. The

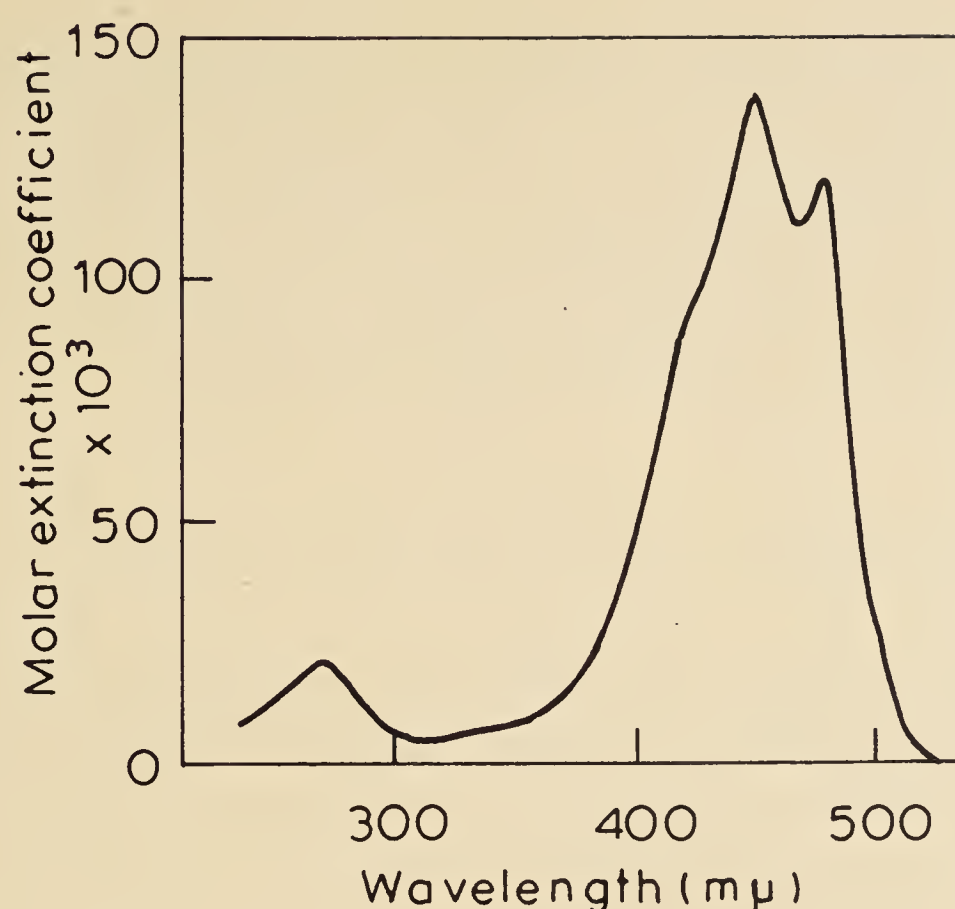


Figure 2. Absorption characteristics of β -carotene.

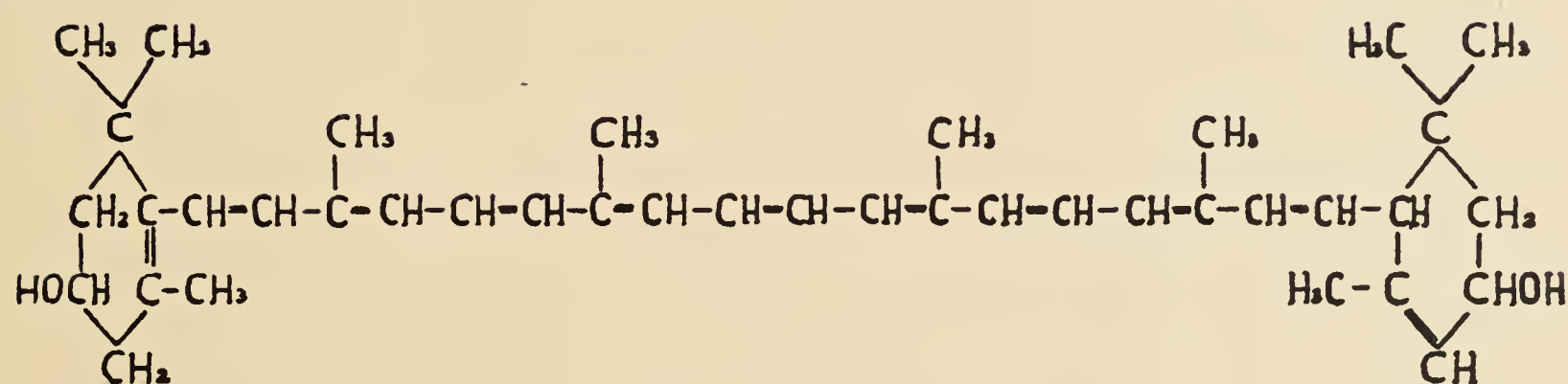


Figure 3. Structure of xanthophyll.

characteristics of the absorption spectrum of xanthophyll in ethanol solution are exhibited by the spectrophotometer curve reproduced in figure 4. It will be seen that xanthophyll resembles β -carotene in its spectroscopic behaviour; but there are significant differences. In particular, the inflexion which appears in the absorption curve of β -carotene shows up as a distinct maximum at the same point in the case of xanthophyll.

The absorption spectra of the carotenoid pigments have been explained as arising from a swinging to and fro of the electrons along the length of their molecules. The incident radiation would excite such an oscillation provided that its electric vector is parallel to the length of the molecule. Simultaneously with the electronic oscillation and as an accompaniment to it, molecular vibrations would also be excited. The energy required for exciting the latter would add up to that of the electronic excitation. Hence the absorption spectrum would spread towards

higher frequencies and smaller wavelengths. Peaks of absorption representing the successive harmonics of the most strongly excited molecular vibration frequencies may be expected to appear. It is thus possible to understand, at least in a qualitative fashion the characteristic features of the absorption curve; firstly, a steep rise at the long-wave end leading up to the first and fairly high maximum; after the first maximum, a few additional maxima and then a slow drop-down to a very weak absorption at the violet end of the spectrum.

3. Xanthophyll and the spectral colour sequence

The colour of the spectrum to any observer with normal colour vision is green at $520\text{ m}\mu$, blue at $480\text{ m}\mu$ and violet at $420\text{ m}\mu$. Referring to figure 4, it will be seen that the absorptive power of xanthophyll is zero at $520\text{ m}\mu$, has reached its first maximum at $480\text{ m}\mu$ and that at $420\text{ m}\mu$ it has passed its third maximum and is on its downward course. If xanthophyll is the visual pigment which functions in the wavelength range between 4000 and 5000 \AA , the change-over from green to blue should appear in the vicinity of the steeply rising part of the absorption curve at about $490\text{ m}\mu$. This, indeed, is what is actually observed; the change of colour with wavelength is shown by the investigations already reviewed in the first part of this memoir to be very rapid in the vicinity of that wavelength. Similarly, one

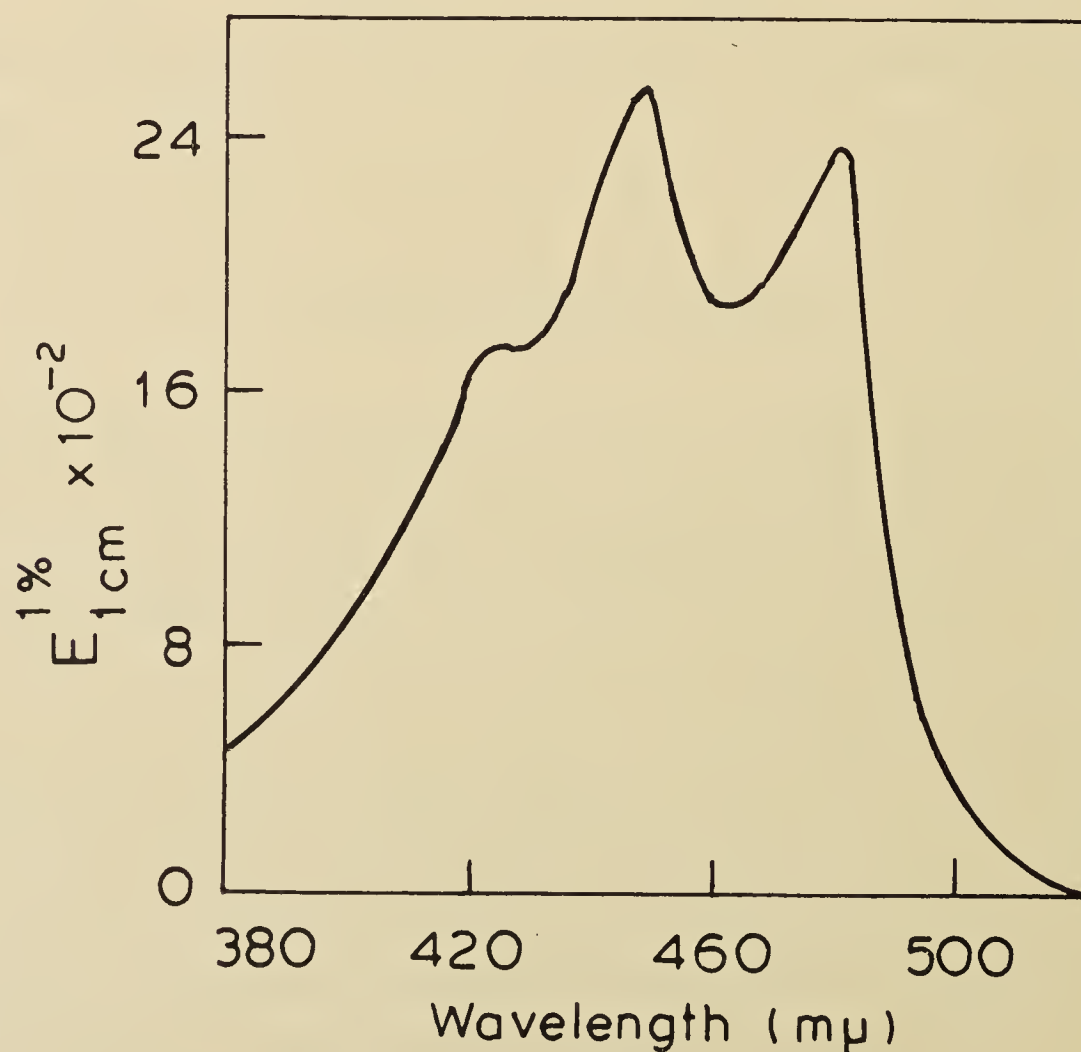


Figure 4. Absorption characteristics of xanthophyll.

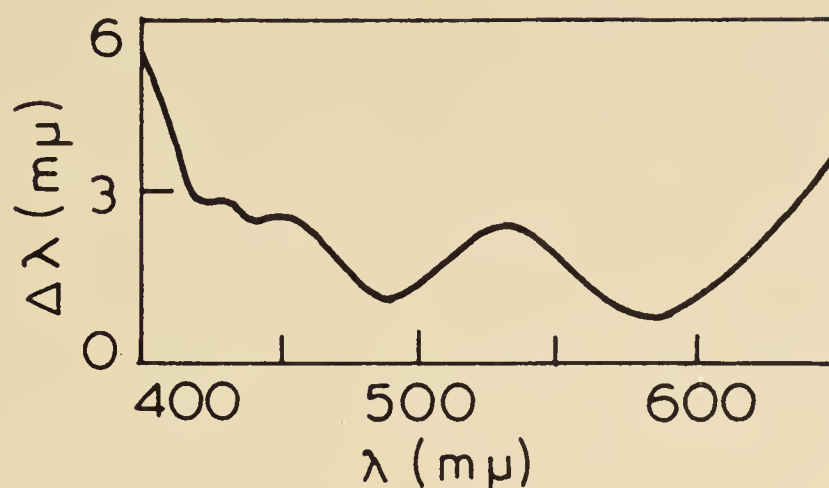


Figure 5. Hue discrimination curve in the spectrum.

would expect the change from blue to violet to occur in the vicinity of the steeply falling part of the absorption curve around 440 $m\mu$. At this wavelength, again, it has been observed that the colour changes rapidly with alteration of wavelength. In other words, the absorption-curve of the visual pigment and the colour sequence in the spectrum exhibit a close correlation, as indeed is to be expected since it is the visual pigment which by its absorptive properties enables the radiation to be perceived.

Figure 5 reproduces the hue discrimination curve in the spectrum which appears on page 229 in the late Dr P J Bouma's posthumously published book entitled *Physical Aspects of Colour*. It is stated that the curve represents the average of the results of a dozen different investigators whose published papers are listed in the book. (Some of these references are not available for consultation at Bangalore.) The graph shows a small dip at 420 $m\mu$ besides the more conspicuous ones at 490 $m\mu$ and 440 $m\mu$, mentioned above. The dip at 420 $m\mu$ appears in the same position as the steep fall in the absorption curve of xanthophyll which commences after it has reached and passed its third maximum.

Besides the features referred to above, the blue-violet region of the spectrum exhibits other observable characteristics which should be mentioned and commented on here. The luminous efficiency which at 500 $m\mu$ is very much less than the maximum appearing in the greenish-yellow part of the spectrum shows a further rapid fall as we proceed towards shorter wavelengths. This feature is represented in figure 6, the observations being those made by Jainski using a flicker method and a retinal illumination high enough to ensure that the results refer to photopic conditions. His observations do not take us beyond 460 $m\mu$. But the simplest visual observations suffice to show that the luminosity of the spectrum becomes very small as we approach further towards its violet end. The other characteristic of the spectrum to which attention may be drawn appears in figure 5 reproduced above. The minimum of wavelength difference perceptible as a colour change exhibits a progressive increase as we approach the violet end of the spectrum, being some five times greater at 400 $m\mu$ than it is at 500 $m\mu$. This

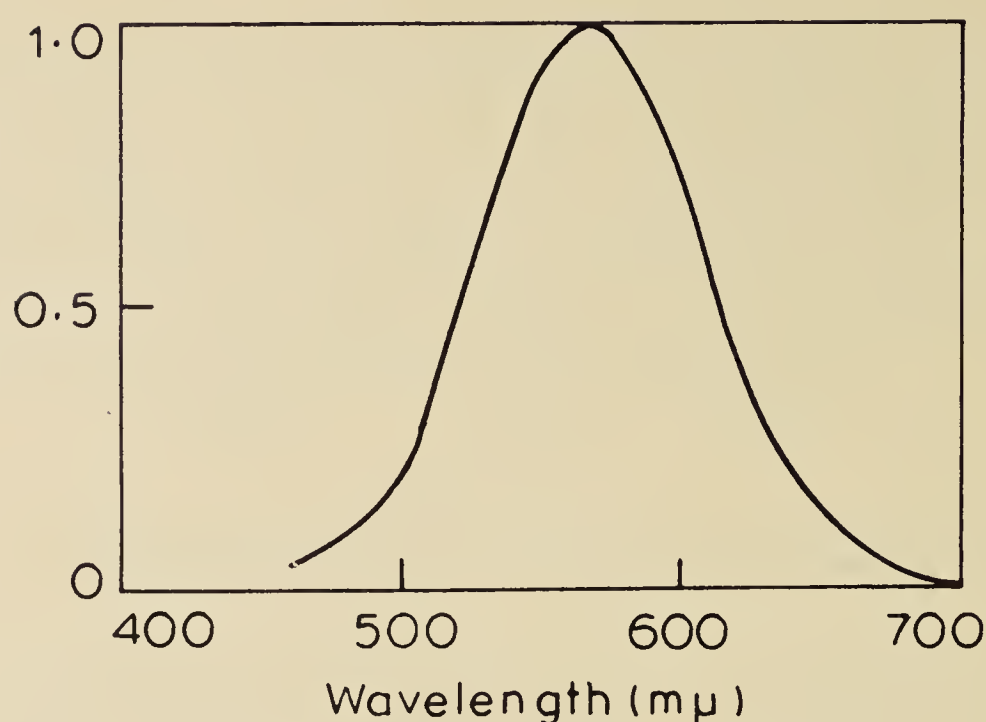


Figure 6. Photopic luminous efficiency curve.

increase accompanies and is superposed upon the undulations in the value of the minimum which appear in the same range of the spectrum. These features of visual experience are clearly related to the absorption characteristics of xanthophyll; the fall of luminous efficiency goes hand in hand with the decrease in absorptive power and the decreasing power of hue discrimination with the diminishing slope of the absorption curve, as we pass from the blue to the violet and approach the end of the visible spectrum.

It appears worthwhile also to mention here that very simple visual observations with a pocket spectroscope and a moderately strong solution of xanthophyll prepared in the manner already stated suffice to establish the principal features in its absorption spectrum. With an absorption cell of small thickness, say 1 cm, one observes an enfeebled transmission in the blue and violet and a succession of absorption maxima in that region. This region exhibits a distinct edge at about 490 mμ beyond which there is free transmission of light. A bluish-green section is visible which precedes the green and the rest of the spectrum. With a greater absorption path, say 3 cm, there is a complete cut-off of the violet and blue regions of the spectrum and a distinct enfeeblement of the bluish-green region. With a large absorption path, say 10 cm, the bluish-green section is also completely cut off, and we observe an absorption edge located at 510 mμ which separates the fully absorbed from the freely transmitted parts of the spectrum.

4. Effects observed with polarised light

We have already had occasion to notice two very striking properties of xanthophyll, viz., the elongated form of its molecules and the restriction placed on

their power to absorb light and therefore also on the power of xanthophyll to function as a visual pigment, viz., that the radiation falling on the molecules should have its electric vibration—or at least a component of it—parallel to the length of the molecules. These properties would have no observable consequences if the molecules of xanthophyll were orientated at random in the retina. This, however, is not the case in the foveal region which exhibits a depression or pit with the foveola at its centre and with sloping sides having a maximum slope angle of about 20° . As a consequence, the nerve fibres in the retina are normal to its surface only at the centre of the pit or depression. Elsewhere they slope away from the normal and as a result, the region of the fovea presents a radially disposed fibrous structure. The xanthophyll molecules are themselves highly elongated bodies and as they are part of the retina, they would naturally set themselves parallel to the elements of the fibrous structure in which they are located. In other words, the visual pigment would present to the incident light a radially disposed array of molecules with their long axes pointing towards the centre of the fovea. This radial disposition would be least evident at the centre of the fovea, would be most conspicuous in the region around the centre where the nerve fibres slope outwards and would cease again to be noticeable outside the foveal region.

If the observer views an extended source of unpolarised light, the special features of the foveal region referred to would not result in anything noticeable. With polarised light, however, the situation would be different. The molecules of xanthophyll which are parallel to the direction of optical vibration would function as absorbers and give rise to the sensation of a bright brush of light along that direction. The molecules perpendicular to the direction of vibration would be unable to absorb the light and hence a dark brush would appear along that direction. In other words, the observer would see an image of his fovea projected

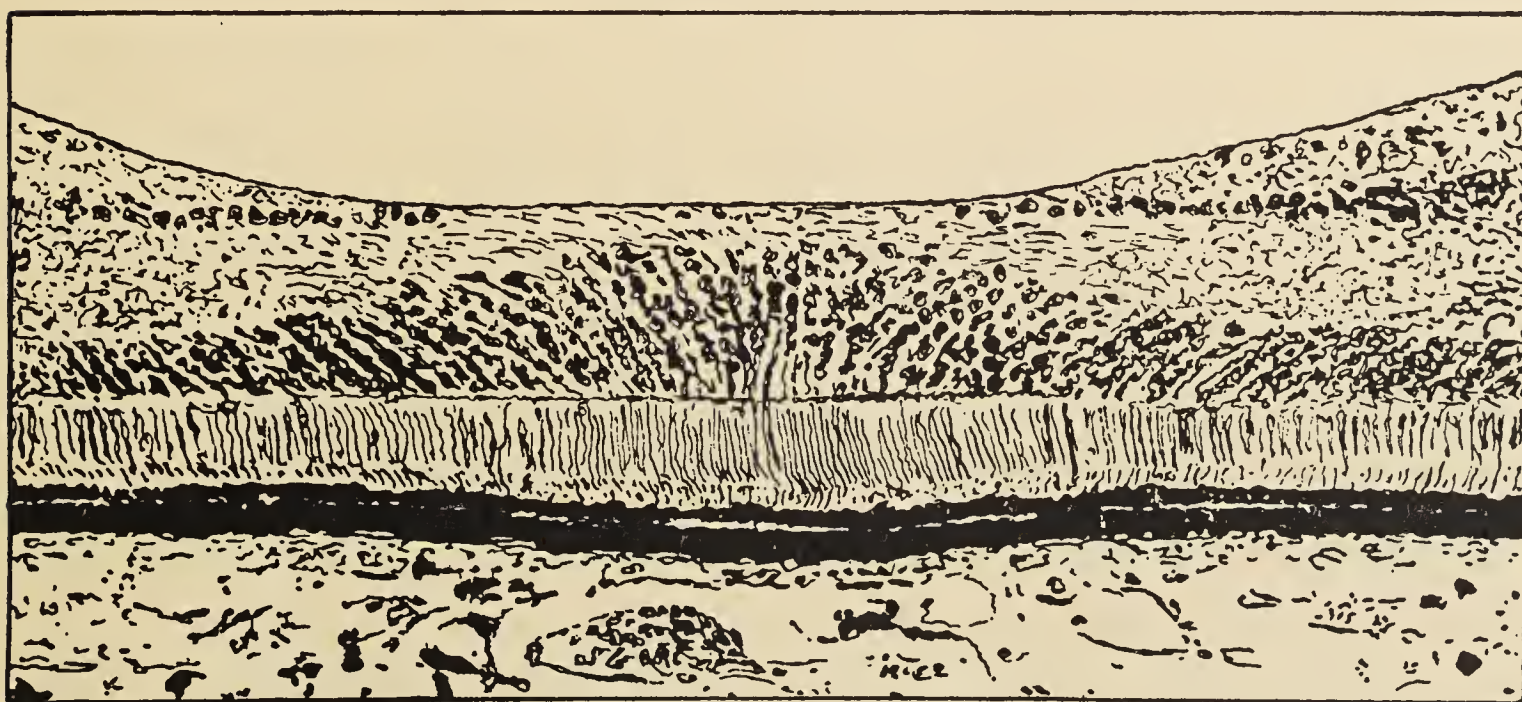


Figure 7. Structure of the foveal region.

in space which presents the aspect of a cross, the arm parallel to the direction of vibration in the incident light being bright and the arm perpendicular to it being dark.

Since the absorption of xanthophyll covers only the violet and blue regions of the spectrum but does not extend to greater wavelengths, it follows that the foveal cross seen in polarised light would be at its best if the incident light lies within those spectral regions. Light of greater wavelengths would not exhibit the phenomenon and hence its presence would only add to the general illumination of the field and thereby make the foveal cross a much less conspicuous phenomenon than it really is. This remark is of special importance in view of the relatively low luminosity of the blue and violet regions in comparison with the rest of the spectrum.

Since xanthophyll is a photopic visual pigment, it follows that the foveal cross requires for its observation that the illumination of the field with polarised light is sufficiently strong to ensure photopic conditions for the spectral region under consideration. When the illumination is reduced and we pass over to scotopic conditions, the effect should weaken and ultimately cease to be observable.

It should also be remarked that the phenomenon of the foveal cross should be equally well or even better seen binocularly as monocularly. For, what is actually observed is a picture of the foveal region projected on the field of view and when both eyes are used, their foveal regions are in register, in other words, both are seen at the same point in space.

It also deserves to be emphasised that the foveal cross seen in polarised light and the picture of the fovea seen with colour filters of various sorts described in the second part of this memoir are closely related phenomena. In both cases we are concerned with a localised excitation of the visual receptors and the possibility of directly perceiving the results of such excitation. The closeness of the analogy will become plainer when we presently take up a description of the methods of observation and the results obtained.

5. Observation of the effects

The phenomenon originally discovered by Haidinger viz., a faint brush which enables the eye to recognize polarised light and ascertain its plane of vibration is ordinarily both inconspicuous and fugitive in character. It however becomes a striking and conspicuous effect in the following circumstances; the field viewed by the observer should be of adequate intensity, e.g., a cumulus cloud lit by sunlight or a brilliantly illuminated white screen; the observer should hold before his eyes (in addition to a polaroid) a colour filter which is transparent to the blue and violet rays and completely cuts out the rest of the spectrum; the polaroid should be rotated, or else oscillated continuously instead of remaining in a fixed orientation. With these arrangements, one observes a dark brush and crossing it

transversely, a bright brush; the dark brush is very dark and the bright brush is brighter than the surrounding field. The two brushes together form the figure of a cross which fills an area which is readily recognizable as a projection in space of the fovea centralis of the observer's own retina. As the polariser is turned round or oscillated, the cross turns round or oscillates synchronously with it around a point which is the projection in space of the foveola of the observer's retina. If the polaroid and colour filter are both large enough, the whole phenomenon can be viewed binocularly.

The importance of using a colour filter which transmits the blue and violet regions of the spectrum and excludes the rest becomes clear when the observer substitutes for it a complementary filter, viz., a yellow glass plate which cuts off the blue and violet regions and transmits freely the rest of the spectrum. *Not a trace of the foveal cross can then be seen.* It follows that the cross owes its origin to a visual pigment whose absorption appears in the violet and blue regions but does not extend to the rest of the spectrum. A more detailed examination may be made in different ways. One can, for example, view through the polaroid a field illuminated by a monochromator and alter the wavelength progressively. Alternatively, we may use the monochromatic radiations of the mercury arc; the brushes are fairly well seen with $\lambda 4538$ and also, but not so well, with the $\lambda 4046$ radiations. A simple method by which the entire spectrum may be scanned is to view the first order spectrum of a linear source of white light produced by a glass diffraction grating held along with a polaroid in front of the observer's eye. The foveal cross can then be seen, if the observer directs his vision to the blue or violet region of the spectrum. But they are not visible in other parts of the spectrum, the transition from invisibility to visibility occurring rather abruptly around 4900 \AA . The cross is clearest in the wavelength region between 4800 and 4300 \AA . It is less distinct at still shorter wavelengths but nevertheless continues to be visible to the violet end of the spectrum.

A technique of observation different from that described above yields highly interesting results. With the colour filter held before his eye, the observer suddenly interposes a polariser in front of it. The cross then comes into view and slowly fades away. After a little while, the observer suddenly removes the polaroid. The cross is then seen once again but rotated through a right angle, the dark arm appearing in the place of the bright arm and *vice-versa*. On putting the polariser back, the cross regains its original configuration; and when the polariser is taken out once again, the cross turns round once again. It is thus clear that a sudden removal of the polaroid produces an effect of the same nature as that of turning it round through a right angle. This effect is clearly analogous to the phenomena observed with colour filters described in the second part of this memoir. The sudden removal of the polaroid results in the component vibration cut off by it being restored and allowed to fall upon the retina. As a consequence, the foveal cross is seen again but turned round through a right angle.

A convenient technique for studying the effects due to polarised light at

different levels of illumination is to use a powerful and completely enclosed source of light, e.g., a mercury arc or a tungsten lamp and to isolate the effective part of its spectral radiation by a colour filter which covers an aperture placed close to the source. The light which issues from the aperture can be received on a translucent diffusing screen and the light emerging through the latter is viewed by the observer through a polaroid from an appropriate distance. If the arrangement is set up in a long darkened chamber, the brightness of the field under observation can be varied over a large range by the simple device of moving the diffusing screen from a position close to the aperture from which the light issues to another sufficiently far away. Observations made in this manner show that the foveal cross is visible only when the illumination which falls on the diffusing screen is strong enough to allow ordinary print to be read. If the illumination be diminished further so that print ceases to be readable, the cross becomes indistinct. When the illumination is so feeble that a printed page appears to the eye as a mere blur, the cross ceases altogether to be visible. The disappearance of the foveal cross thus goes hand in hand with the disappearance of the visual acuity which is a characteristic of photopic vision. It is also observed that the field of view as seen through the polaroid shows a progressive change in colour from a brilliant blue to a pale blue as the illumination is diminished to the point at which the foveal cross ceases to be noticeable. This is a further indication that we have then moved out from the photopic to the scotopic level of illumination in the blue and violet regions of the spectrum.

The perception of light and colour and the physiology of vision—Part IV. Ferroheme and ferriheme

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1. Introduction

In the first part of this memoir, the basic facts concerning the perception of light and colour were reviewed and a mechanism of the functioning of the retina was suggested which explains them in a simple and intelligible fashion. Human vision is mediated by certain pigments present in the retina, these pigments acting as energy-receiving and energy-transferring agents; in other words, they absorb the quanta of radiational energy incident on the retina, but pass on the energy thus absorbed to the sensory mechanism, themselves returning to their original states. The second part of the memoir dealt with the problem of determining the number and nature of the visual pigments functioning in the manner indicated, the regions of the spectrum in which they respectively operate and the distribution of the pigments over the area of the retina. A method of observation was described which furnishes valuable information on these points. Considerations were also developed which pointed to xanthophyll, ferroheme and ferriheme as the three visual pigments with which we are concerned in photopic vision. In the third part of the memoir, evidence was presented which confirms and establishes that xanthophyll is the visual pigment which functions in the violet and blue regions of the spectrum.

In the present part of the memoir, we are concerned with the region of the spectrum between the wavelengths 5000 and 7000 Å. The facts of observation which concern us here and need interpretation are firstly, the distribution of luminosity in this region of the spectrum; secondly, the distribution of colour in it; and thirdly, a derivative property of the same, namely, the characteristics of the colour progression which find expression in the so-called hue discrimination curves determined by various observers. We shall consider these facts here in some detail and discuss their interpretation. The aim is to infer therefrom the spectroscopic behaviour of the visual pigments and to compare the same with what is known regarding the absorption spectra of the heme pigments.

2. Luminosity, colour and hue discrimination

The form of the luminous efficiency curve in the spectrum depends to a notable extent on the region of the retina used in its determination. In what follows, we shall make use of the data obtained by Walters and Wright under photopic conditions in which only the foveal region of the retina was employed. Their results are reproduced below in figure 1. It will be noticed that the luminous efficiency exhibits a well-defined maximum at 5600 Å on either side of which it descends steeply, but less rapidly so on the side of longer wavelengths than towards the shorter ones. This pronounced asymmetry of form evidently calls for explanation.

The graph of the luminous efficiency reproduced in figure 1 may be divided into four parts which exhibit distinctly different characters: (i) the foot of the graph from 4400 to 4950 Å where it exhibits a marked curvature; (ii) the steeply ascending part from 4950 to 5600 Å; (iii) the steeply descending part from 5600 to 6270 Å; (iv) the foot of the graph from 6270 to 7000 Å where again it exhibits a marked curvature.

On the basis of the average positions of the colour boundaries in the spectrum as placed by observers with normal vision, we may divide the visible spectrum into four sectors thus: blue-violet, $\lambda < 495 \text{ m}\mu$; green, $495 \text{ m}\mu < \lambda < 566 \text{ m}\mu$; orange-yellow, $566 \text{ m}\mu < \lambda < 627 \text{ m}\mu$; and red, $627 \text{ m}\mu < \lambda$. It will be noticed that these sectors represent also the divisions of the luminous efficiency curve

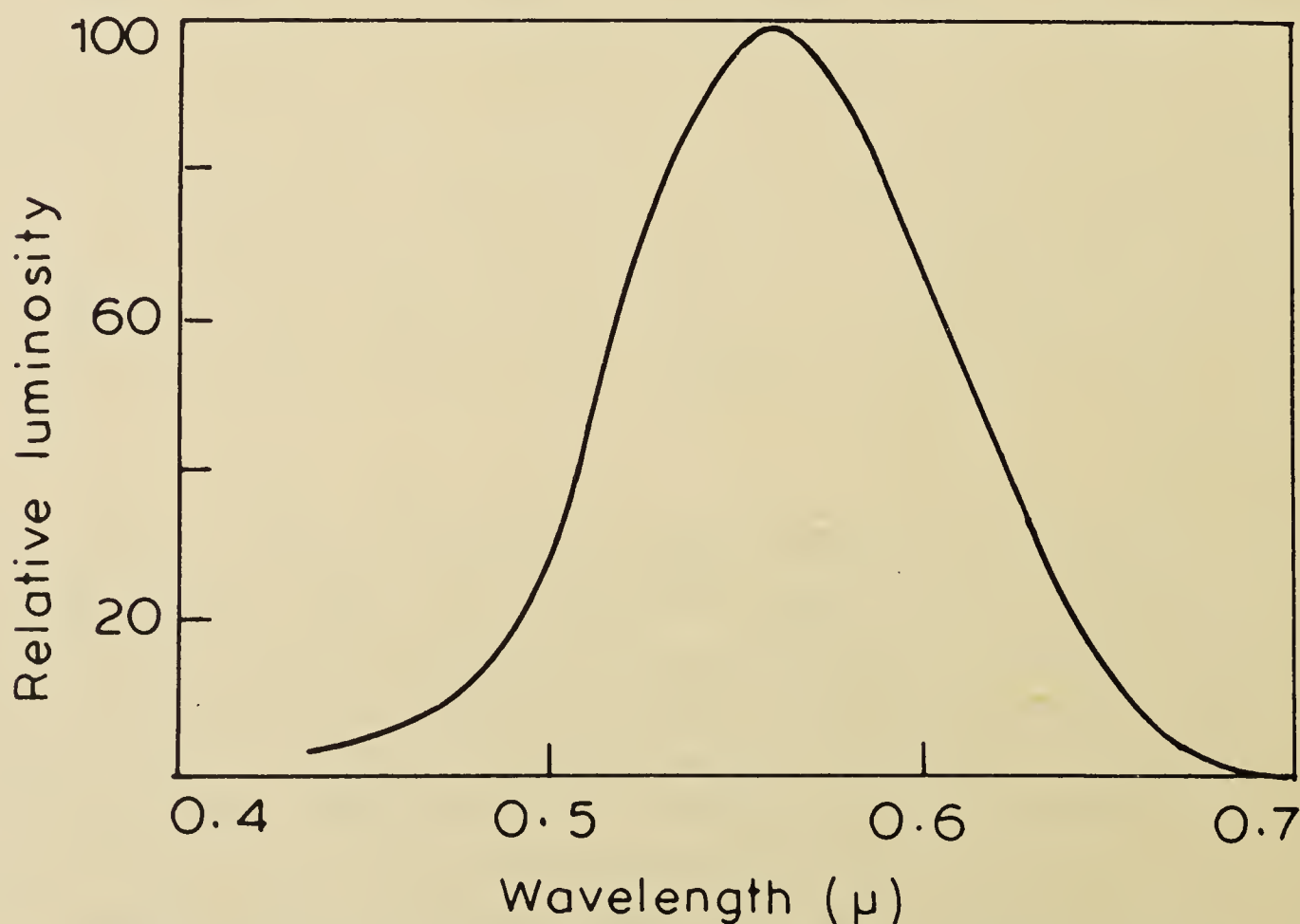


Figure 1. Foveal luminous efficiency curve according to Walters and Wright.

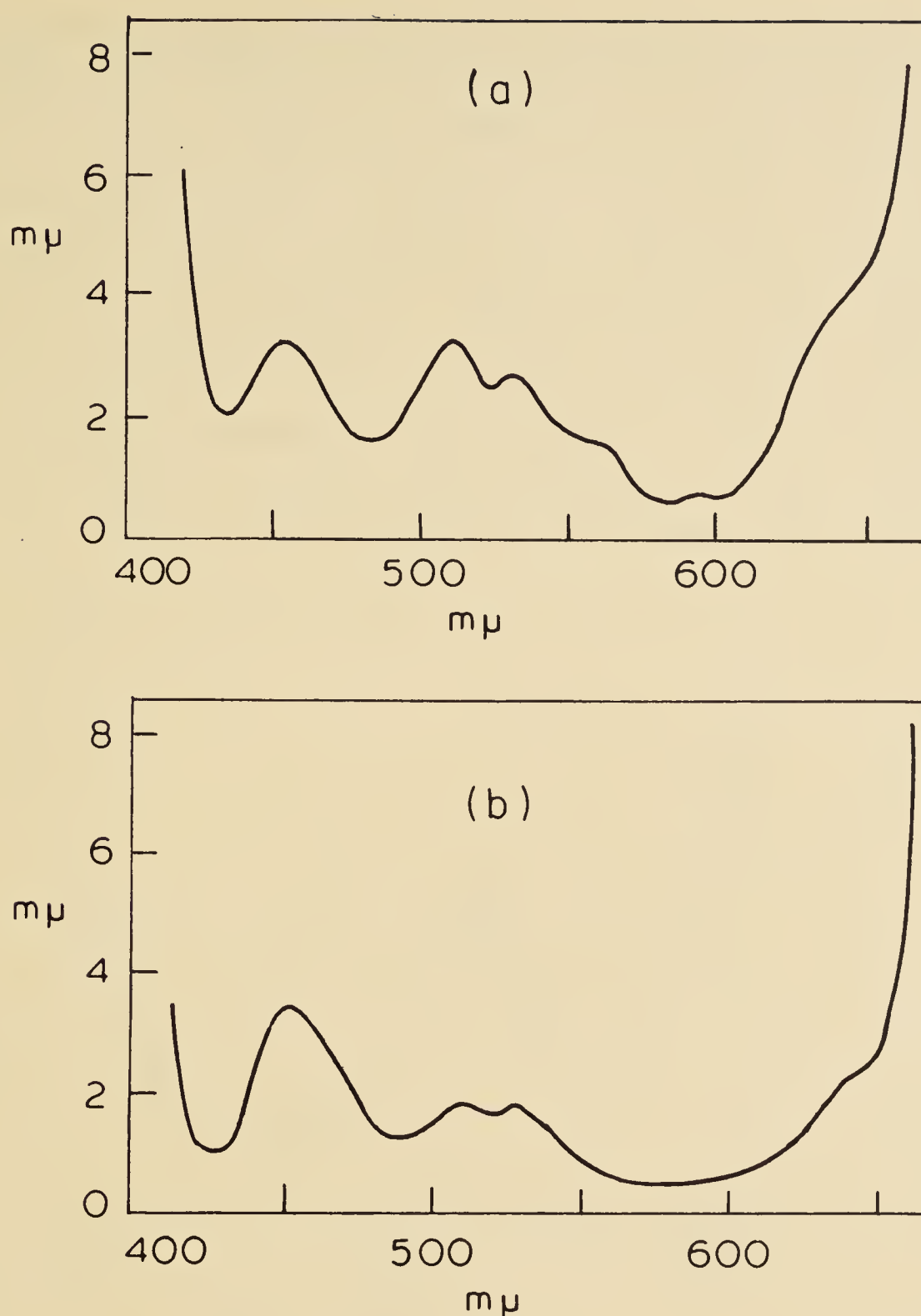


Figure 2. Hue discrimination in the spectrum (after Haase).

indicated above, except that the green-yellow boundary is placed at 566 $m\mu$ instead of 560 $m\mu$ where the maximum luminous efficiency appears.

Measurements of the smallest change of wavelength needed for a perceptible change of colour have been made and reported by numerous observers. Their results agree in respect of the major features but show some differences in detail. This is not surprising, since the characteristics of human vision are by no means the same for all observers, and the techniques and physical conditions of observation are also not identical in all the investigations. Two slightly different forms of these hue discrimination curves have already been reproduced in earlier parts of this memoir. Figure 2 above represent the results reported by Haase for two different levels of illumination, figure 2(b) representing the results for the

higher level of the two which was ten times greater in intensity than the other. Figure 3 below reproduces the results of E.P.T. Tyndall for the wavelength range between 450 and 650 $m\mu$. The individual observations made by him at various times are marked in the graph by crosses and circles and show a remarkable consistency except in the vicinity of the humps at 530 and 630 $m\mu$ respectively.

Tyndall's observations place the wavelength of minimum limen at 575 $m\mu$ where it has the value of 0.5 $m\mu$; at greater wavelengths it increases, at first quite slowly and then more and more rapidly, reaching large values at the red end of the spectrum. The results reported by Haase and shown in figure 2 exhibit generally similar features in the same region. At the wavelengths around 530 $m\mu$ where Tyndall's data exhibit a considerable scatter, Haase's results show two minor humps instead of the single hump at 535 $m\mu$ reported by others.

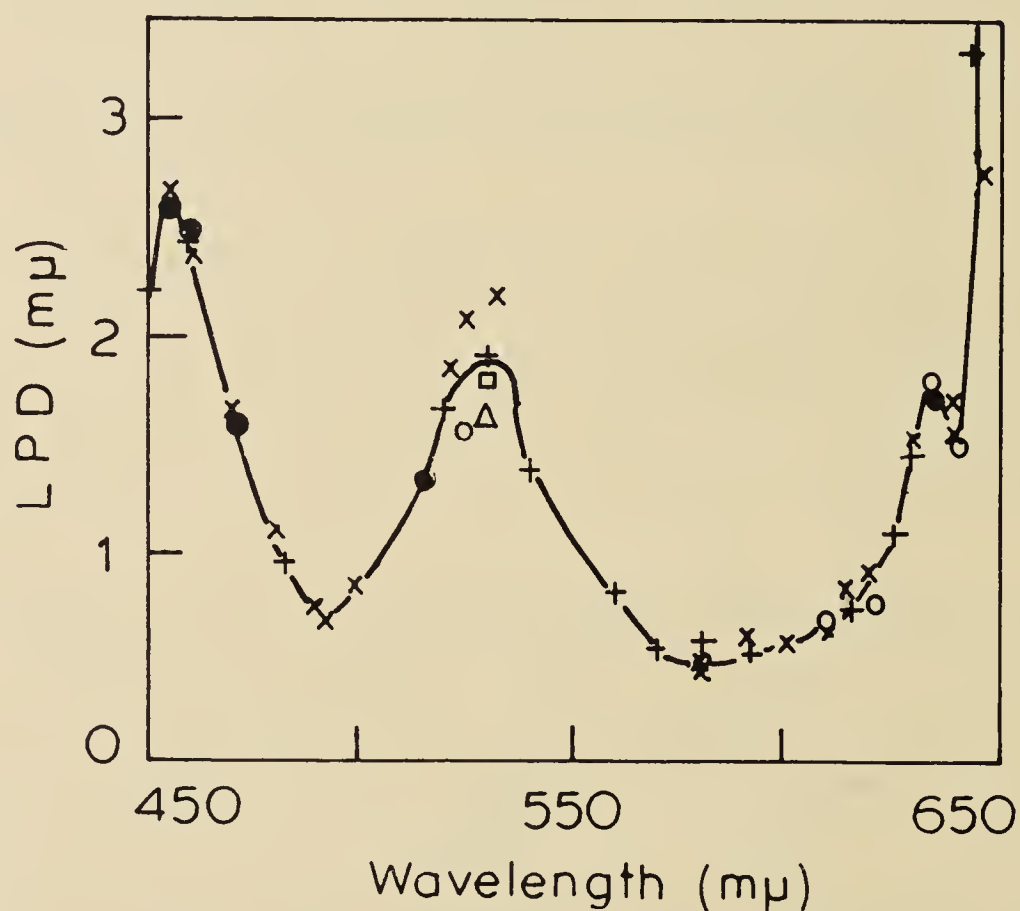


Figure 3. Hue discrimination curve (after E.P.T. Tyndall).

3. The colour sequence in the spectrum

The luminous efficiency curve reproduced in figure 1 above represents a summation of the effects of the three visual pigments functioning in their respective regions of the spectrum. It gives no indication of any special features related to those appearing in the hue discrimination curve at various points in the spectrum. We have therefore to assume that any special features appearing in the absorption curves of the individual pigments which determine their respective luminous efficiencies have been smoothed out and rendered unobservable by

reason of such summation. However, since the second visual pigment which functions in the green sector of the spectrum plays the major role in human vision, we are justified in assuming that the pronounced maximum at $560\text{ m}\mu$ exhibited by the luminous efficiency curve arises principally by reason of a very conspicuous maximum at or near the same wavelength in the absorption spectrum of that pigment. On the other hand, in the blue-violet region of the spectrum, the first visual pigment which functions in that region would principally be responsible for the observed luminous efficiency. Likewise, the third visual pigment would be responsible for the observed luminosity in the region of longer wavelengths and its extension in that direction would account for the asymmetric form of the luminous efficiency curve.

The experiments and observations described in the second part of this memoir showed very clearly that there is a considerable overlap in the absorption spectra of the second and third visual pigments. That there is such an overlap and that it has a most important effect on the visual sensations excited by light appearing in the regions of such overlap is the clue to an understanding of the facts set forth above regarding the distribution of colour in the region of the spectrum now under consideration. The luminous efficiency curve itself indicates that there is a large drop in the absorptive power of the second visual pigment at wavelengths greater than $560\text{ m}\mu$ and we may safely assume that this drop continues over the whole range in which that curve goes steeply down, in other words, up to about $627\text{ m}\mu$. The colour change from green to yellow, from yellow to orange and then from orange to red appears precisely in this region. It is a justifiable inference that these changes are a consequence of a rapid falling off in the luminous effect due to the second visual pigment and its progressive replacement by the luminous effect of the third visual pigment which, though inherently much weaker than that of the second pigment, nevertheless effectively determines the observed visual sensations in the regions of the spectrum where it is relatively more important. Continuing this line of argument, we infer that when, at about $627\text{ m}\mu$, the colour of the spectrum passes over from orange to red, the second visual pigment has ceased to be effective, in other words, that its absorption strength is practically zero. On the other hand, the luminous efficiency curve itself indicates that the visual effect due to the third pigment persists up to the extreme red end of the spectrum, slowly and progressively decreasing with increasing wavelength.

4. Hue discrimination in the spectrum

The mechanism of the perception of light and colour by the eye which was indicated in the first part of the memoir was based on the quantum theory of radiation. It recognizes that the physical basis for the differences in colour perceived by the eye in the different parts of the spectrum is the fact that the magnitudes of the light-quanta differ from one end of the visible spectrum to the

other, being least at the red end and greatest at the violet. To account for the remarkably high power of discrimination of colour actually exhibited by our eyes, it was postulated that the visual pigments in the retina which are the mediators of vision absorb the energy quanta incident on them and immediately pass on the energy thus absorbed to the sensory mechanism and return to their original energy states. Accepting this hypothesis, the following two questions arise which require an answer: What is the factor which limits the power of the eye to discriminate differences in colour in different parts of the spectrum? Why is it as great as it is in some parts, and why is it less in others? We shall now endeavour to find answers to these questions.

As is well known, the absorption of light by molecules embedded in solid or liquid media is manifested in the form of diffuse spectral bands exhibiting only remnants of the structure shown by their spectra in the state of vapour. As a typical example, we may mention the absorption spectrum of toluene in hexane solution observed in the near ultra-violet. Some nineteen bands are indeed discernible in the region between 270 and 240 $m\mu$, but only the first few of them are sharp and intense, and as we proceed further into the ultra-violet, they become weaker and more diffuse, and the individual bands can only with difficulty be distinguished apart from each other.

The absorption of light by the molecules of the visual pigments embedded in the retina and the transfer of the absorbed energy to the sensory mechanism would necessarily be influenced by various factors, including especially the thermal agitation in the medium. The absorption of radiation involves the electronic energy levels of the molecules of the pigment and the vibrational levels coupled with them. Thermal agitation, on the other hand, appears as the energy of translatory movements. In solid and liquid media, the molecules may be regarded as being continuously in a state of collision, and hence exchanges of translatory energy *may* occur simultaneously with the exchanges of electronic and vibrational energy. Whether this happens at all and the extent to which it occurs may be expected to depend on the circumstances of each particular case. To obtain a rough idea of the effect of such exchanges, we proceed on the basis of the highly simplified picture of the process indicated by the following equation

$$h\nu - h\nu^* \approx \pm kT,$$

in which h , k , and T are respectively Planck's constant, Boltzmann's constant and the absolute temperature of the retina, while $h\nu$ is the energy of the light incident on it and duly absorbed and $h\nu^*$ is the energy actually transferred to the sensory mechanism. The plus and minus signs refer to the cases in which the energy transferred is respectively diminished and increased by the presence of thermal agitation.

Taking

$$h = 6.62 \times 10^{-27} \text{ erg. sec.}$$

$$k = 1.38 \times 10^{-16} \text{ erg. deg.}^{-1}$$
$$T = 310^{\circ}$$

($\nu - \nu^*$) when expressed as wave-numbers comes out as ± 215 . In other words, the precision with which the eye can recognize a variation in the magnitude of the light quantum as a variation in colour in the spectrum would be diminished to the extent of 430 wave-numbers. When expressed as a wavelength spread in millimicrons, it comes out as directly proportional to the square of the wavelength in the spectrum, in other words, some four times greater at the red end of the spectrum than at the violet end. The calculated figures are shown in table 1 below.

Table 1. Effect of thermal agitation on hue discrimination

Spectral region in $m\mu$	750	700	650	600	550	500	450	400
Spectral spread in $m\mu$	24	20	18	16	12	10	8	6

Comparing the figures shown in table 1 with the actual facts of observation as reported by various investigators, it is immediately obvious that except at the extreme red and extreme violet ends of the spectrum, the eye actually exhibits a power to detect changes of colour with change of wavelength far in excess of that indicated by the calculations appearing in table 1. Especially in certain parts of the spectrum, viz., around 440, 490 and 590 $m\mu$, one finds a remarkable and obviously highly significant sensitivity to colour change with wavelength which closely approaches the theoretical perfection indicated by the principles of the quantum theory when the effect of thermal agitation is ignored. The inference is obvious, viz., that the manner of calculation adopted greatly overestimates the influence of thermal agitation on hue discrimination. The transference of radiational energy to the sensory mechanism which takes place at the retina through the medium of the absorbing pigments present in it is presumably a very rapid process, and it is by no means inevitable that it would be influenced by the thermal agitation in the medium in the manner and to the extent contemplated in the calculations.

We are thus compelled by the facts to approach the subject of the varying power of the hue discrimination in the spectrum from a different standpoint. We may reasonably expect it to be closely related to specific features in the absorption spectra of the visual pigments functioning in the respective regions of the visible spectrum; these features are not necessarily observable in the luminous efficiency curve, being masked by reason of the superposition of the effects of all three pigments in it. In the hue discrimination curve, on the other hand, they may well be expected to manifest themselves. In other words, the form of the hue

discrimination curve is an indicator of the features of the absorption spectra of the individual pigments and is thus of prime importance in relation to the physiology of vision.

Already, in the third part of this memoir, it has been shown that the form of the hue discrimination curve in the blue-violet sector of the spectrum stands in the closest relationship to the special features in the absorption spectrum of the visual pigment functioning in that sector, viz., xanthophyll. The minima of the limen of wavelength change for a perceptible alteration in colour appearing around 490 and 440 $m\mu$ were, in fact, explained as due to the steep ascent and descent appearing in the absorption spectrum of xanthophyll respectively at those wavelengths. It is evident that we have likewise to seek for the explanation of the very remarkable minimum of limen noticeable in the wavelength region around 590 $m\mu$ on a similar basis.

Earlier, it has been remarked that the drop of the luminous efficiency at wavelengths greater than that of its maximum at 560 $m\mu$ should be ascribed to a steep drop in the absorptive power of the second visual pigment in that region. Indeed, the latter drop should evidently be even steeper than that of the luminous efficiency curve. For, in the latter curve, the effect of the third visual pigment is superposed and since the latter evidently diminishes with increasing wavelength in this region, the steepness in the drop of the luminous efficiency curve would be diminished by reason of such superposition. We are thus entirely justified in inferring that in the region of wavelengths greater than 560 $m\mu$, the second visual pigment exhibits a very steep drop in absorption with the result that it is practically negligible at wavelengths greater than 625 $m\mu$. Accordingly, in the region of wavelengths between 560 and 625 $m\mu$, we should expect the limen for colour discrimination to exhibit a large diminution and that it should reach its lowest value in the region of wavelengths somewhere between those limits where the absorption curve of the second visual pigment exhibits its steepest fall, viz., around 590 $m\mu$. This is what is actually observed to be the case. The two D lines of sodium appear in this vicinity, and it is a well-established experimental result that when these two lines are equalised in their intensity, they exhibit an observable difference in colour.

5. The absorption spectra of the heme pigments

The considerations of a general nature which lead us to the identification of the two visual pigments functioning in the green and red sectors of the spectrum as ferroheme and ferriheme respectively have already been set out in the second part of this memoir. We shall, in what follows, review the known facts regarding the absorption of light by the heme pigments with a view to compare them with the behaviour of the retinal pigments as indicated by the facts of visual experience.

The iron-protoporphyrin complex known as heme appears associated with

different proteins in biological material. The extraordinary versatility which heme exhibits in performing a variety of physiological functions is ascribable to its association with the appropriate proteins in the different circumstances. Extensive studies have appeared in the literature regarding the absorption spectra which it exhibits in various cases. Indeed, the identification of the different heme proteins in biochemical research is largely based on their spectroscopic behaviour. The absorption of light by the heme proteins owes its origin in the first instance to the special structure characteristic of the porphyrin group of compounds, viz., the tetrapyrrolic group containing a closed ring of eighteen bonds which are alternately single and double. The character of the absorption is however modified when a metal atom enters the porphyrin structure and finds its place at the centre of the ring. Further modifications in the spectroscopic behaviour appear when the metal-porphyrin structure associates itself with other nitrogenous materials, including especially different proteins.

The porphyrins when dissolved in organic solvents exhibit a typical four-banded absorption in the visible spectrum with some indications of further details. The strength of the bands increases towards shorter wavelengths and in addition there is a still stronger band at about $400\text{ m}\mu$ known as the Soret band, having been first observed by that author in the absorption spectrum of hemoglobin. The four bands of protoporphyrin, for example, in ether-acetic acid solution have their maxima at 632, 576, 537 and $502\text{ m}\mu$ respectively, while indications of subsidiary bands at 605 and $585\text{ m}\mu$ have also been noticed. It is worthy of remark that at the temperature of liquid air, the bands sharpen and are partly split up and shifted to shorter wavelengths.

The spectroscopic behaviour of the porphyrins in the form of complex salts formed by their combination with different metals has been extensively investigated, using the synthetically prepared substances in solution in different organic solvents. Generally speaking, it is found that the four-banded spectrum of the porphyrins is replaced by a two-banded spectrum, the position of the two maxima as well as their relative intensity varying with the metal which has entered the structure of the porphyrin. Ferrocoproporphyrin, for example, shows a strong absorption band at $550\text{ m}\mu$ and a weak one at $520\text{ m}\mu$. The great difference between the spectroscopic behaviour of the complexes formed by the combination with iron in the ferrous and ferric states may be illustrated by the case of mesoporphyrin. Whereas the ferrous compound with it exhibits, in a buffered acetic acid solution, a band covering the region 555 to $565\text{ m}\mu$ in the green, the ferric compound shows two bands, one in the green between 530 and $542\text{ m}\mu$ and another in the red between 630 and $640\text{ m}\mu$.

The association of the iron-porphyrin complexes with other nitrogenous substances to form what are known as hemochromes and hemichromes respectively has a notable influence on the character of their absorption spectra. The hemochrome structure is characterised by the appearance of a two-banded absorption spectrum of which the first or α -band is very sharp and also much

more intense than the second or β -band of shorter wavelength. The positions of these two bands are observably influenced both by the nitrogenous base and by the porphyrin. In the hemochrome formed by protoporphyrin with pyridine for example, the α -band has its maximum at $558\text{ m}\mu$, while the β -band appears at $525\text{ m}\mu$. On the other hand, the hemochrome formed by the combination of ferrous iron with mesoporphyrin and pyridine has its absorption maxima at $547\text{ m}\mu$ and $518\text{ m}\mu$.

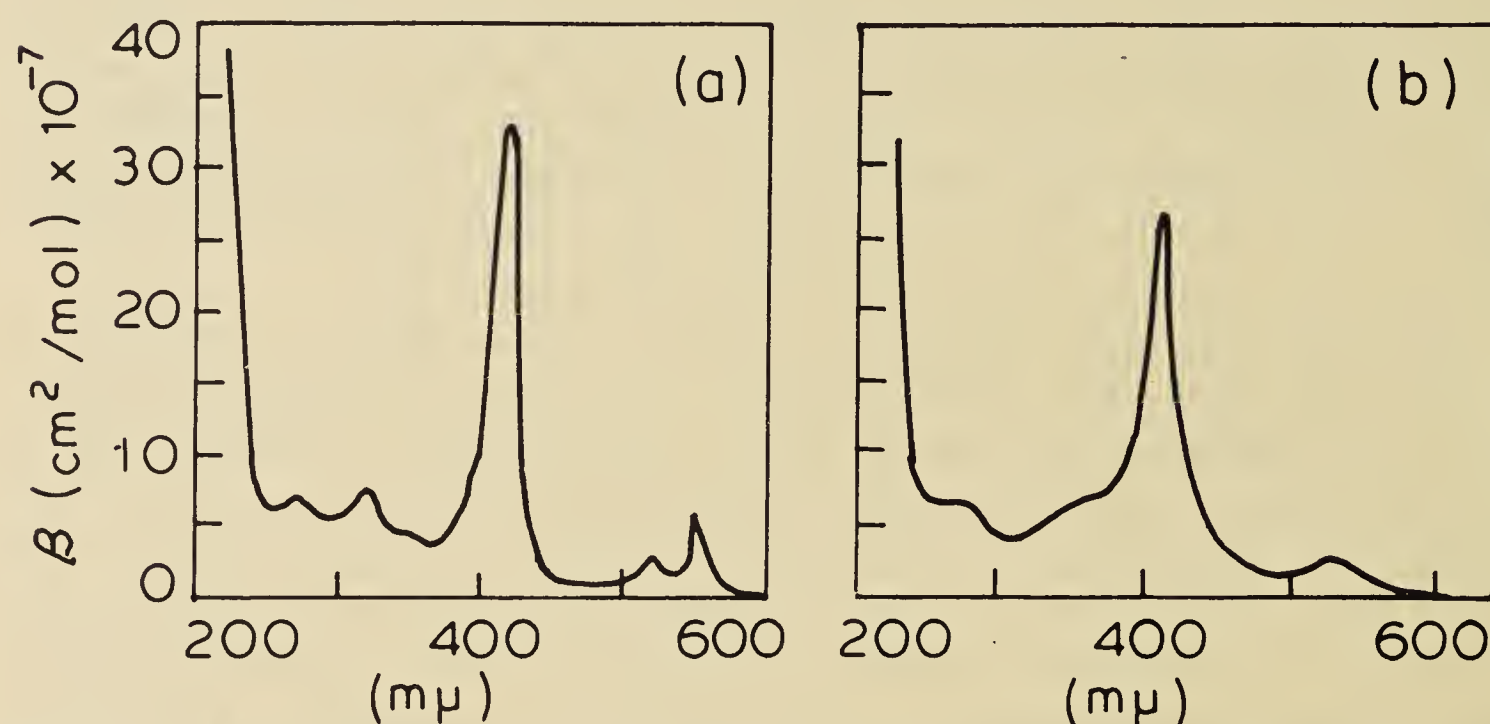


Figure 4. (a) Ferrocyclochrome. (b) Ferricytochrome. Absorption spectra of cytochrome *c* after (Theorell).

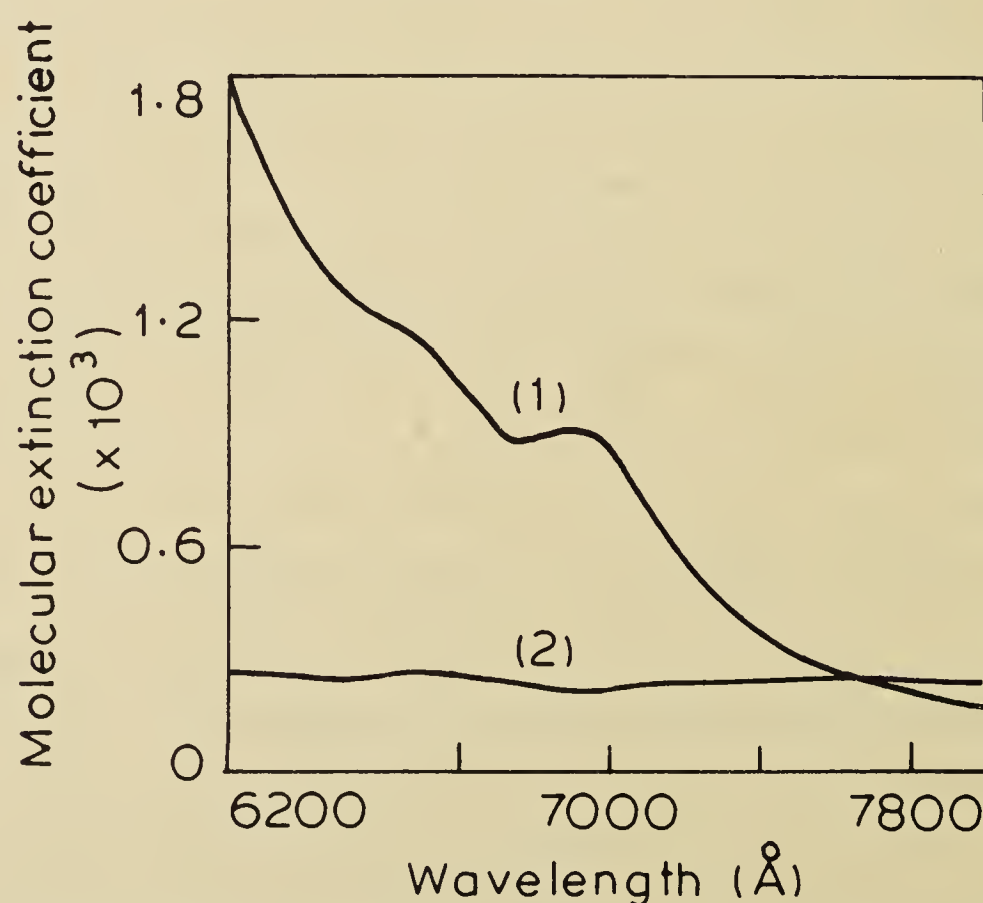


Figure 5. Absorption spectrum of cytochrome *c* in the extreme red. (1), Oxidised form; (2), reduced form.

A reference should also be made here to the absorption spectra of the cytochromes, of which several have been reported and which are distinguished from each other by their spectroscopic behaviour. The best-known of them is cytochrome *c* which has been isolated and spectroscopically investigated in the pure state. It shows absorption maxima at 550 and 521 $m\mu$, the former or α -band being the more intense of the two. Figure 4 below reproduces the absorption characteristics of cytochrome *c* as determined by Theorell.

Figure 4(a) represents that of the reduced form, viz., ferrocytochrome *c* and figure 4(b) that of the oxidised form, viz., ferricytochrome *c*. It will be noticed that while the absorption by the ferrous pigment exhibits a strong, sharp band located at 550 $m\mu$ and a weaker one at 521 $m\mu$ and is practically confined to the green region of the spectrum, the ferric compound has an absorption extending into the red with a broad diffuse maximum in the green around 530 $m\mu$. This difference between the ferrous and ferric forms is further illustrated in figure 5 (due to Horecker and Kornberg) which shows that the absorption by the latter goes right up to the extreme red end of the spectrum.

6. The observable consequences

If white light is spread out into a spectrum of small dispersion by a diffraction grating, the latter appears to the eye to consist of three bands of colour of approximately equal width: a blue-violet band which is highly colourful but of low luminosity and covers the region from 400 to 500 $m\mu$; a green band for 500 to 600 $m\mu$ and a red band from 600 to 700 $m\mu$. The two latter bands are also colourful, the red perhaps more so than the green, but the red is less luminous, especially near the extremity of the spectrum. The yellow-orange section of the spectrum appears merely as an edging between the green and red. The most luminous part of the spectrum is in the green, not far from its yellow edge. The rapid changes in colour from blue to green at about 490 $m\mu$, and from yellow to orange at about 590 $m\mu$ are also obvious to inspection. One is tempted to associate the three principal bands of colour with three visual pigments functioning in three distinct regions of the spectrum. But the appearance of the yellow and orange as a transition between green and red is a clear indication that there is an overlap of the absorption spectra of the second and third visual pigments.

The various related features of the spectrum mentioned above are readily intelligible in the light of the spectroscopic behaviour of the heme pigments discussed in the foregoing pages. The pigments formed by the combination of ferrous iron with protoporphyrin absorb light in the region of wavelengths between 500 and 600 $m\mu$. In all cases, the maximum of this absorption appears at or near 650 $m\mu$ which is also the wavelength of maximum luminous efficiency in the spectrum. Then again, the absorption drops down quickly with increasing

wavelength between 560 and 600 $m\mu$. This feature explains the low values for the limen of hue discrimination observed in that region. The absorption by the ferric forms of the pigment, on the other hand, appears both in the green and red sectors of the spectrum; it is, however, weaker and more diffuse than that of the ferrous forms. This situation explains the appearance of yellow and orange as transition colours between the green and the red in the region where the absorption by the second pigment is weak. Likewise, the diffuseness of the absorption by the ferric pigment and its progressive weakening with increasing wavelength explain the diminishing luminosity and the increasing limen of hue discrimination as we approach the red end of the spectrum.

Some remarks should be made here regarding the Soret band of absorption. Had this been effective as a mediator in human vision, the violet end instead of being the feeblest part of the spectrum, would have been the most luminous. The inference is obvious, that the Soret band is not active as a transmitter of the energy absorbed which, presumably, is dissipated in some other fashion.

The Soret band is a general feature in the absorption spectra of the whole porphyrin group of compounds, even when a metal atom is not present at the centre of the tetrapyrrolic group. There is therefore no reason to believe that it would act in the same way as the absorption bands in the visible region appearing by reason of the presence of the metal atom. It may be remarked in this connection that chlorophyll participates in the photosynthetic activity of green leaves by reason of its characteristic absorption band in the red; the Soret band, so far as is known, remains entirely inactive.

The perception of light and colour and the physiology of vision—Part V. The colour triangle

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1. Introduction

So far, in this memoir, we have concerned ourselves exclusively with the sensations excited by monochromatic radiations of different wavelengths appearing in the spectrum. The reason for this, as has already been explained in the first part of the memoir, is that only by such an approach is it possible to reach a correct understanding of the nature of the retinal processes which enable us to perceive light and colour. We shall now turn to the consideration of the more complex field which offers itself in the study of the sensations excited by heterogeneous light. Here again, the visual sensations resulting from monochromatic light necessarily form the starting-point of our approach to the subject. Indeed, the outstanding result which has emerged from all investigations in this field is the relation that all observed colours bear to the colours of monochromatic radiation. These latter stand in a category by themselves and form a kind of upper limit to the visual manifestations of colour.

The functioning of the three visual pigments present in the retina in their respective spectral regions will form the basis of our considerations. It will be shown that they enable a satisfactory elucidation to be given of the observed facts of the subject including especially those which in the past have been sought to be interpreted or explained in terms of the so-called trichromatic theory of vision. It is necessary here to emphasise that for a full understanding of the facts of heterochromatic vision, the role played by the central parts of the organ of sight is no less important than the functioning of the retina which is only the periphery of that organ. The function of the retina is to receive, absorb and pass on the energy of the incident radiation. But the synthesis which enables composite radiation consisting of energy quanta of different magnitudes to be perceived as a visual sensation can only take place in the central part of the visual organ. This is indeed very clear from the facts of binocular vision. There is no colour sensation which can be produced by mixing two lights and presenting them to one eye which cannot be duplicated by supplying the two lights independently, one to each eye.

As an example of this general principle, it will suffice to mention the familiar techniques employed in colour stereoscopy.

2. The chromatic sensations

As we proceed, it will emerge that the sensations which result from the superposition of radiations appearing in different parts of the spectrum fall into two categories which we shall term the *chromatic* and *achromatic* sensations respectively. We shall commence with a consideration of the chromatic sensations. The colours of the spectrum which represent the effect of monochromatic radiations on our visual organs are, of course, the chromatic sensations of the first order. In certain circumstances, however, the superposition of different monochromatic radiations may result in colour sensations which may be included in that category. We shall now consider these cases in order.

A group of cases of particular importance is that in which two radiations appearing respectively at the two ends of the spectrum, viz., violet and red, are superposed. The observations described in the second part of this memoir show that the visual pigments which function at the two ends of the spectrum are *exclusively* the first and the third respectively. The energy-quanta at the red and violet ends of the spectrum also differ widely. There is no reason, therefore, to anticipate that the spectral components of the incident radiation would be confused with each other when the signals originating at the retina reach the cerebrum. Indeed, in this case, human vision very nearly succeeds in recognising the composite nature of the incident radiation. That the so-called purples are a mixture of red and violet is fairly obvious even to an inexperienced observer. The relative intensities of the two components make themselves felt in the hues perceived which form a complete sequence ranging from red at one end to violet at the other and rival the pure colours of the spectrum in their brilliance. It follows that the purples can be classed with the colours of monochromatic light as chromatic sensations of the first order. It is evident also that a mixture of two purples in any proportion would give us only another purple, in other words, nothing essentially different.

Another set of cases of special importance is that in which the two monochromatic radiations which are superposed both lie within the range of wavelengths between 530 and 780 m μ . Xanthophyll which is the visual pigment functioning in the violet and blue sectors of the spectrum does not absorb any light of wavelengths greater than 530 m μ . Hence, in the region between 530 and 780 m μ , only two visual pigments, viz., ferroheme and ferriheme function. The observations described in the second part of the memoir show clearly that there is a considerable overlap in their absorption spectra. It follows that when red and green radiations from the two ends of the range are superposed in any proportion, the resultant sensation would be one of the spectral colours falling within the

same range. Indeed, two monochromatic radiations from anywhere between these wavelengths when superposed would reproduce a spectral colour lying elsewhere in the same range. These indeed are facts. They emerged quite clearly from Clerk Maxwell's investigations with his colour box and have been confirmed by all later investigations.

There is yet a third class of cases in which the superposition of monochromatic radiations gives rise to a chromatic sensation, viz., those in which the superposed radiations are close to each other anywhere in the spectrum. They may be sufficiently far apart to be perceived as different in colour when viewed separately or in adjacent fields. Yet, when they are superposed, the eye fails to recognise the composite nature of the light and perceives a colour which may be described as the colour of a spectral frequency which is the weighted average of the frequencies of the superposed radiations, the weightage being determined by their respective luminosities.

3. The achromatic sensation

A spectroscopist would define white light as a stream of radiation which comprises energy-quanta of all possible values ranging over the entire visible spectrum and with an energy distribution such as would be found in the radiation from a black body at very high temperatures. Since, however, the central organ of vision is incapable of resolving the incident radiation into its spectral components, there is no reason for assuming that only such a radiation would be perceived by the eye as white light. Indeed, much less stringent requirements might suffice. We may remark here that the light falling on the retina is absorbed by three visual pigments which between them cover the entire range of the visible spectrum. Hence, the minimum requirement for the perception of the incident heterogeneous radiation as white light could well be the following: *all the three visual pigments should function and should contribute to the observed luminosity in the same proportions as they would if the incident radiation were white light in the spectroscopic sense.* We shall provisionally accept this requirement as adequate and compare its consequences with the actual facts of observation.

The green light appearing in the wavelength region between 495 and 566 m μ stands in a category by itself. In this sector of the spectrum, vision is mediated almost exclusively by ferroheme though the other two visual pigments make sensible contributions respectively near the two ends of the sector. It follows that to achromatise green light, one would require the addition of radiations from both ends of the spectrum where xanthophyll and ferriheme respectively function. The complementaries to the green of the spectrum accordingly lie in the region of the purples; as we pass from the boundary between blue and green to the boundary between green and yellow, the location of the complementary colour would shift from the red to the violet end of the series of purples.

As has been remarked earlier, the yellow colour of the spectrum between 566 and 589 $m\mu$ and the orange colour between 589 and 627 $m\mu$ arise by reason of the circumstance that the absorption spectra of ferroheme and ferriheme overlap in these regions; in the yellow sector, their absorptions are of comparable strength, while in the orange, the third pigment is distinctly the more effective. As a consequence of this, the complementary colour to yellow would be at the violet end of the spectrum; as we move into the orange, the complementary colour would shift into the blue. A further shift towards the red would result in the complementary colour being located at the boundary between the green and blue sectors in the spectrum. The remarkable fact of observation that in a whole series of cases the superposition of only two monochromatic radiations with appropriate intensities results in a complete suppression of colour thus finds a simple and satisfactory elucidation on the basis of the present approach to colour theory.

4. Superposition of the chromatic and achromatic sensations

We have seen that in certain cases, non-homogeneous light excites chromatic sensations identical with the colours of the spectrum or the purples derived therefrom, while in other cases the resulting sensation is achromatic. We may therefore assume that, in general, both of these effects would be manifested but to different extents depending on the particular circumstance of each case. In other words, the sensation excited by non-homogeneous light could, in general, be described as a superposition of the chromatic and achromatic sensations. The colours of the spectrum and the purples accordingly set an upper limit to the visual manifestations of colour. We infer that non-homogeneous light exhibits a third attribute besides luminosity and colour, namely, the purity or degree of saturation of the colour. The highest purity is that of the pure spectral colours and the purples derived therefrom, while the lowest purity represents the case in which the achromatic part is relatively so large that no colour is discernible. Hand in hand with the concept of purity enters also the concept of dominant wavelength, which is the particular wavelength in the spectrum the colour of which the composite radiation under study most nearly resembles.

An interesting question arises here. Should the chromatic and achromatic sensations associated with non-homogeneous light be regarded as distinct effects or as inseparable from each other? If one thinks in physical terms, there is clearly a fundamental difference between them. An achromatic sensation would correspond to a chaotic and characterless disturbance; on the other hand, a pure spectral colour is associated with specifiable quanta of radiational energy. There is no reason why sensations so different in their nature and origin should be placed in the same category. It seems more appropriate to regard them as quite distinct attributes of the sensations excited by non-homogeneous light.

The very interesting results obtained by E.P.T. Tyndall and by G. Haase in

their studies on colour discrimination with admixtures of monochromatic and white light have a bearing on the issue raised above. Measurements were made by these authors of the smallest change in wavelength of monochromatic light necessary to produce a detectable change of colour. The determinations were then repeated when white light was added in equal amounts to the two monochromatic fields of slightly different wavelength under comparison, the purity or degree of saturation of the colour in these fields being thus varied in different observations over a wide range. The remarkable result emerged that the chromatic sensibility of the eye to wavelength differences is not significantly diminished even when the white light added represents a 50% dilution of the visible colour. A result of this nature could scarcely have been anticipated unless the chromatic and achromatic sensations are distinct and unrelated effects.

6. The results of colour-mixing experiments

The simplest kind of experiment that could be made on the mixing of colours is to have only two monochromatic radiations, the spectral position and relative intensities of which could be varied, and to compare the sensation resulting from their superposition with another monochromatic radiation appearing in an intermediate position in the spectrum, the intensity of which can also be varied. The results of such comparison can be broadly indicated in the light of the remarks made above.

If both the selected radiations lie within the wavelength range between 530 and 780 $m\mu$, there would be little difficulty in obtaining a perfect match. Likewise, if one of the selected radiations is near the extreme red end or near the extreme violet end, and the other also lies in the violet or red sector of the spectrum as the case may be, there should be no difficulty in matching the result with some intermediate radiation. The situation would however be different if one of the selected radiations lies in the wavelength range between 400 and 530 $m\mu$ and the other also lies in that range, but not in an adjacent position. Only when the two selected radiations are quite close to each other that it would be possible to obtain a good match. The further away they are, the less and less satisfactory would be the result, until finally when the two are sufficiently far apart, there could be no comparison at all. The position would be far worse if one of the radiations is in the wavelength range between 400 and 530 $m\mu$ and the other is in the range between 530 and 750 $m\mu$. We would then be approaching a situation in which the result of mixing the two monochromatic colours would be to obtain an achromatic sensation.

Figures 1 and 2 represent the results of experiments of the same nature as that indicated above with the difference that three instead of two monochromatic radiations were chosen and employed and while their positions in the spectrum were kept fixed, their intensities were varied with a view to obtain a match with

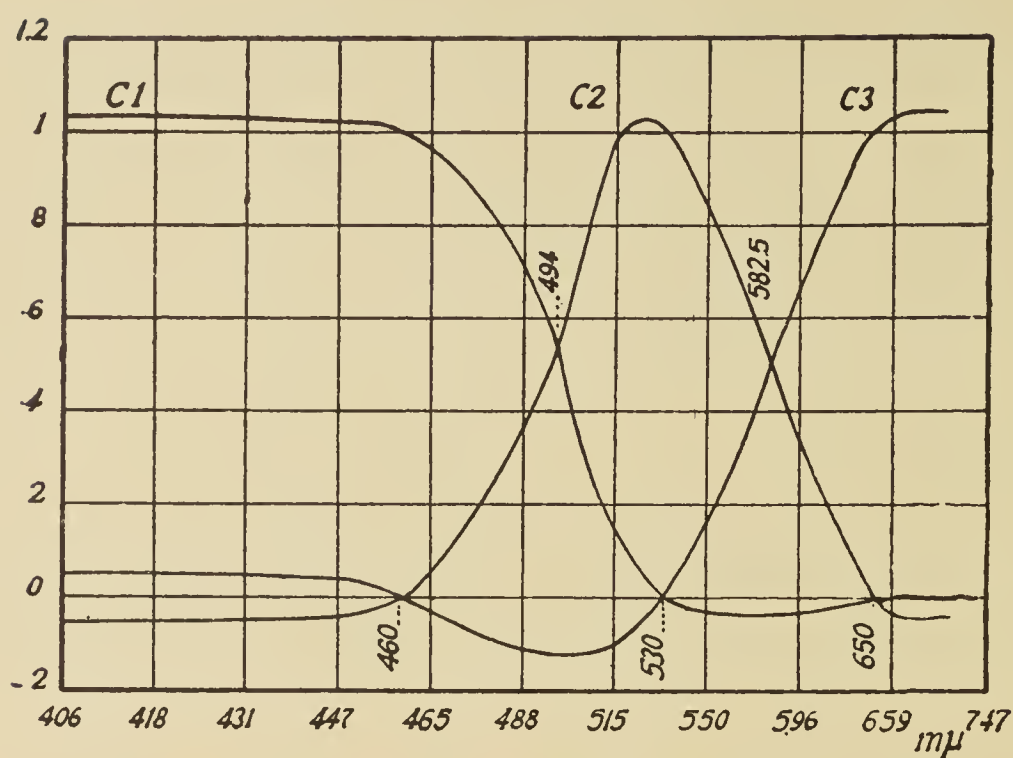


Figure 1. Results of mixing 460, 530 and 650 $m\mu$.

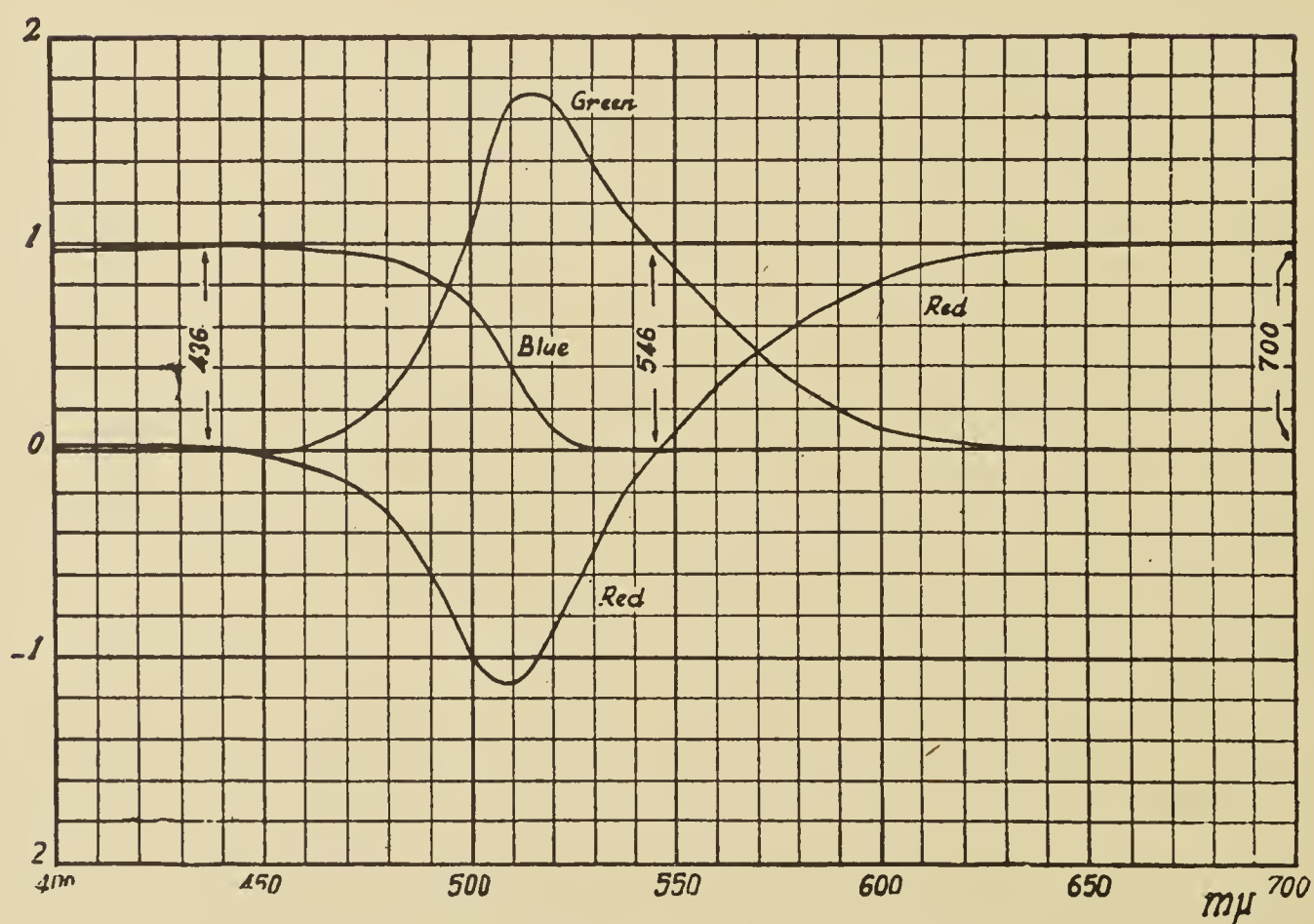


Figure 2. Results of mixing 436, 546 and 700 $m\mu$.

the spectral colours appearing over the whole range of the spectrum. In figure 1, the three chosen wavelengths were 460, 530 and 650 $m\mu$ and the results represented are those of W D Wright and collaborators. In figure 2, the chosen wavelengths were 436, 546 and 700 $m\mu$, the two former being the strong lines in the mercury arc spectrum. The graphs appearing in the figure represent the values of the coefficients C_1 (blue), C_2 (green) and C_3 (red) which indicate the quantities

of blue, green and red light necessary to obtain the match represented by the colour equation

$$C_1B + C_2G + C_3R = \text{Chosen spectral colour,}$$

where

$$C_1 + C_2 + C_3 = 1.$$

Figures 1 and 2 show certain features in common and also some noteworthy differences. We shall first mention the former and remark on their significance in relation to the absorptive properties of the visual pigments. In both figures, the coefficient C_1 (blue) has a value of nearly unity in the violet sector of the spectrum and then drops down steeply in the wavelength range 480 to 530 m μ and is negligible or zero at all wavelengths greater than 530 m μ . The behaviour of C_1 thus clearly follows the absorption characteristics of xanthophyll. Then again, in both figures, the graphs for C_2 (green) and C_3 (red) overlap in the wavelength region between 550 and 625 m μ ; C_2 diminishes and C_3 increases in this range, the graphs crossing at 582 m μ in figure 1 and at 570 m μ in figure 2. C_2 becomes negligible in comparison with C_3 at all wavelengths greater than 625 m μ , while C_3 is dominant and practically unity in that region. Here, again, the behaviours of C_2 and C_3 recall the remarks made earlier regarding the overlapping of the absorption spectra of ferroheme and of ferriheme and its consequences.

The appearance of negative coefficients for C_3 in the spectral region between 460 and 530 m μ is a well-marked feature in both figures but far more so in figure 2 than in figure 1, evidently because the blue and green radiations superposed were farther apart in the spectrum in the case of figure 2 than of figure 1. The appearance of these negative coefficients indicates that the superposition of the two monochromatic radiations results in a strong achromatic component in the sensation. A good measure of the third component has therefore to be added to the spectral colour under study to obtain a colour match. The production of an achromatic sensation by the superposition of monochromatic radiations in certain circumstances is thus an important and indeed basic feature in colour theory. The circumstances in which the achromatic sensation appears have already been discussed in section 3 above and need not therefore be repeated here.

7. Geometric representations of colour

Figure 3 reproduces the so-called XYZ chromaticity diagram. This represents in geometric form certain empirically determined colour relationships which have been put into a shape convenient for practical use. The diagram is reproduced here for the reason that the facts concerning colour vision elucidated in the preceding pages are evident on a simple inspection of it.

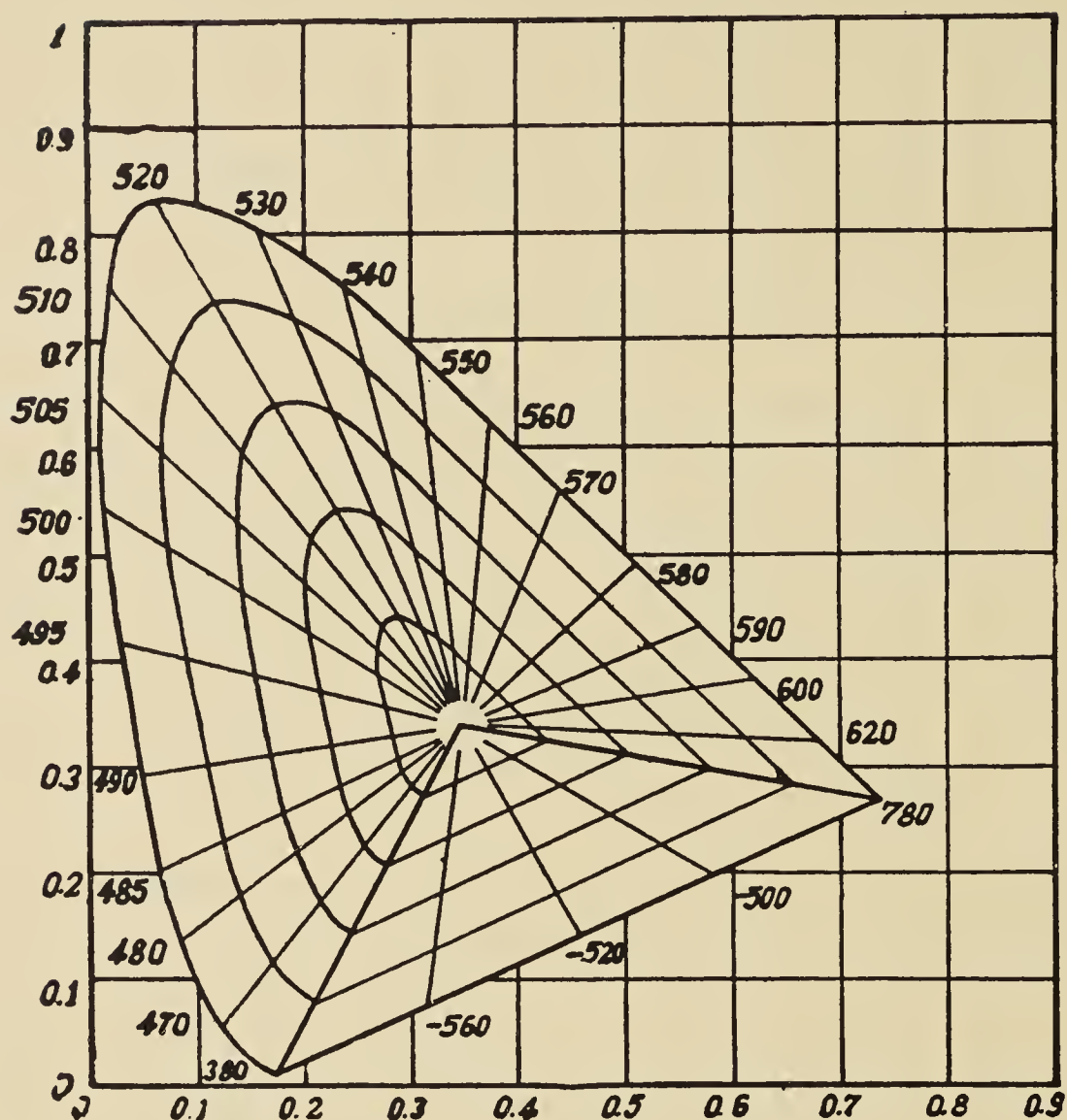


Figure 3. The XYZ chromaticity diagram.

1. All observable colours appear as points inside a closed figure at the periphery of which appear the colours of the spectrum and the line of purples. The latter is a straight line joining the violet and red ends of the spectrum.
2. The spectral colours in the range between 530 and 780 $m\mu$ appear on a line which is straight except very near 530 $m\mu$ where it exhibits a slight curvature.
3. Chromatic sensations complementary to each other are indicated by the two points on the periphery of the figure the straight line joining which passes through its white centre.
4. The degree of saturation or purity of any observed colour is indicated by its position in the figure on the line which joins the white centre with the point on the periphery representing the dominant wavelength.

The perception of light and colour and the physiology of vision—Part VI. Defective colour vision

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1. Introduction

The subject of defects in colour vision is one of very general interest. The actual nature of the defects, the different types of defect and the relationships between them, the hereditary character of the defects, the frequency of their appearance in the human population and their distribution as between the sexes, the manner in which they can be brought to light and their relationship to occupational fitness are some of its different aspects. The scientific investigation of the characters of defective colour vision is a necessary preliminary to a deeper understanding of its nature and origin. In view of the many-sided nature of the subject, it has naturally been the theme of numerous studies and researches and an extensive literature has grown up dealing with it from different points of view.

In the present memoir, we shall concern ourselves chiefly with the fundamental aspects of defective colour vision. The subject will be dealt with on the basis of the ideas set forth and developed in the preceding parts of the memoir.

2. The origin of the defects

The defects of colour vision which we shall proceed to discuss in detail are of congenital origin and belong to the so-called sex-linked and recessive type of inheritable characters. The principles of genetics indicate, in agreement with observation, that defective colour vision should be far less common amongst women than amongst men; usually the woman acts simply as a carrier and transmits the defect without showing any characteristic anomaly herself. The fact that the defects are passed on from parents to progeny is of deep import and suggests that they stand in the closest relationship to the functioning of biochemical processes in the human body. In this connection, it is appropriate here to recall other inheritable characters which are clearly of a biochemical nature. The blood group to which an individual belongs is one of them. Another is

the rare condition known as haemophilia, which is the failure of human blood to stop flowing out from a wound when a person has been accidentally injured. This is known to be a sex-linked recessive defect.

By far the commonest and most thoroughly studied defects in colour vision are those which relate to the perception of the light appearing in the region of the spectrum between 495 and 780 $m\mu$, in other words those covered by the green, yellow, orange and red sectors in the spectrum as perceived by a person with normal colour vision. In this region, as we have seen, vision is mediated by the two visual pigments ferroheme and ferriheme. These have similar structures which differ only in that the iron atom appearing at the central position of the tetrapyrrolic group in one case is in the ferrous and in the other in the ferric state. The question naturally arises as to the nature of the biochemical mechanism which regulates the proportion in which the two pigments appear in the retina. The passage from the ferrous to the ferric state is a change in valency and may be regarded as an oxidative process. It is to be presumed that there is a mechanism at work by which the formation of the ferric pigment is permitted up to a certain proportion and its further progress beyond that point is inhibited.

If the suggestion made above represents the actual position, it follows that the mechanism might, at least in some cases, not function in the normal manner. For example, it is possible that the oxidation is totally inhibited, in which case only ferroheme would be present in the retina. Then again, there might be cases intermediate between such a complete inhibition and the normal functioning of the mechanism. It is also possible that there might be a lack of balance in the opposite direction and some cases in which the oxidation goes so far that ferriheme is in excess of that needed for normal colour vision.

In what follows, we shall consider the consequences of the biochemical situations indicated above and compare them with the actual facts elicited by studies of the different types of defective colour vision.

3. Protanopic and protanomalous vision

The cases of defective colour perception which came first under notice and received the largest share of attention were naturally those of the extreme kind which revealed themselves without any special efforts being made to discover them. Subsequently, however, scientific studies showed that the incidence of the defects is larger than was suspected and that there is a considerable variation in the actual magnitude and character of the defects. At the present time, if we leave aside some rarer types, the kinds of colour vision which have been recognized and investigated are five in number; I. Protanopic vision (1%). II. Protanomalous vision (1%). III. Normal vision (92%). IV. Deuteranomalous vision (5%). V. Deuteranopic vision (1%). The approximate percentages of the male human population belonging to these classes have been entered in round figures after

each of them. The first and the fifth kinds are usually grouped together as dichromatism, while the second and fourth are commonly referred to as anomalous trichromatism, in other words as variants of normal vision.

We shall first consider protanopic vision. Its characters may be deduced from those of normal colour vision discussed in detail in the fourth part of this memoir. In the absence of ferriheme, the distribution of luminosity in the spectrum, the colour sequence observed and the form of the hue discrimination curve would all be necessarily disturbed. The luminosity would be zero in the sector of the spectrum between 650 and 780 $m\mu$ and would be diminished relatively to the rest in the regions of the spectrum where ferriheme, when present, contributes to the observed luminosity. The red sector would disappear completely from the spectrum. In normal vision, ferroheme and ferriheme co-operate in the regions where yellow and orange are seen, and hence in the absence of ferriheme these colours cannot be perceived. Protanopic vision which operates by the mediation of only two pigments, namely, xanthophyll and ferroheme, would accordingly present only two sectors in the spectrum, one on either side of the wavelength 495 $m\mu$ which forms the boundary between blue and green in the normal colour sequence. Hence, as in normal vision, that wavelength would continue to be the

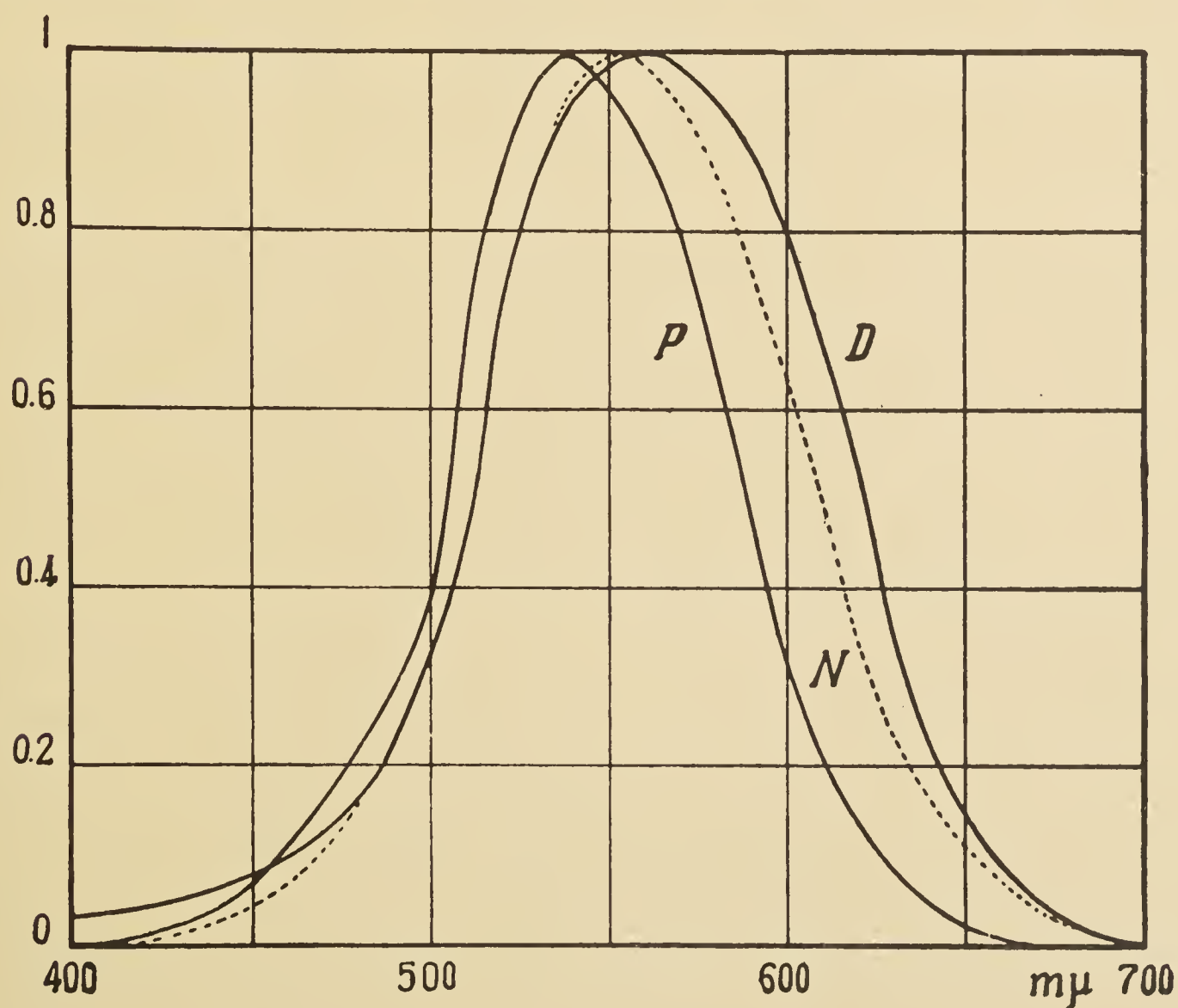


Figure 1. Comparison of spectral luminosity curves for protanopic (P), deuteranopic (D) and normal vision (N).

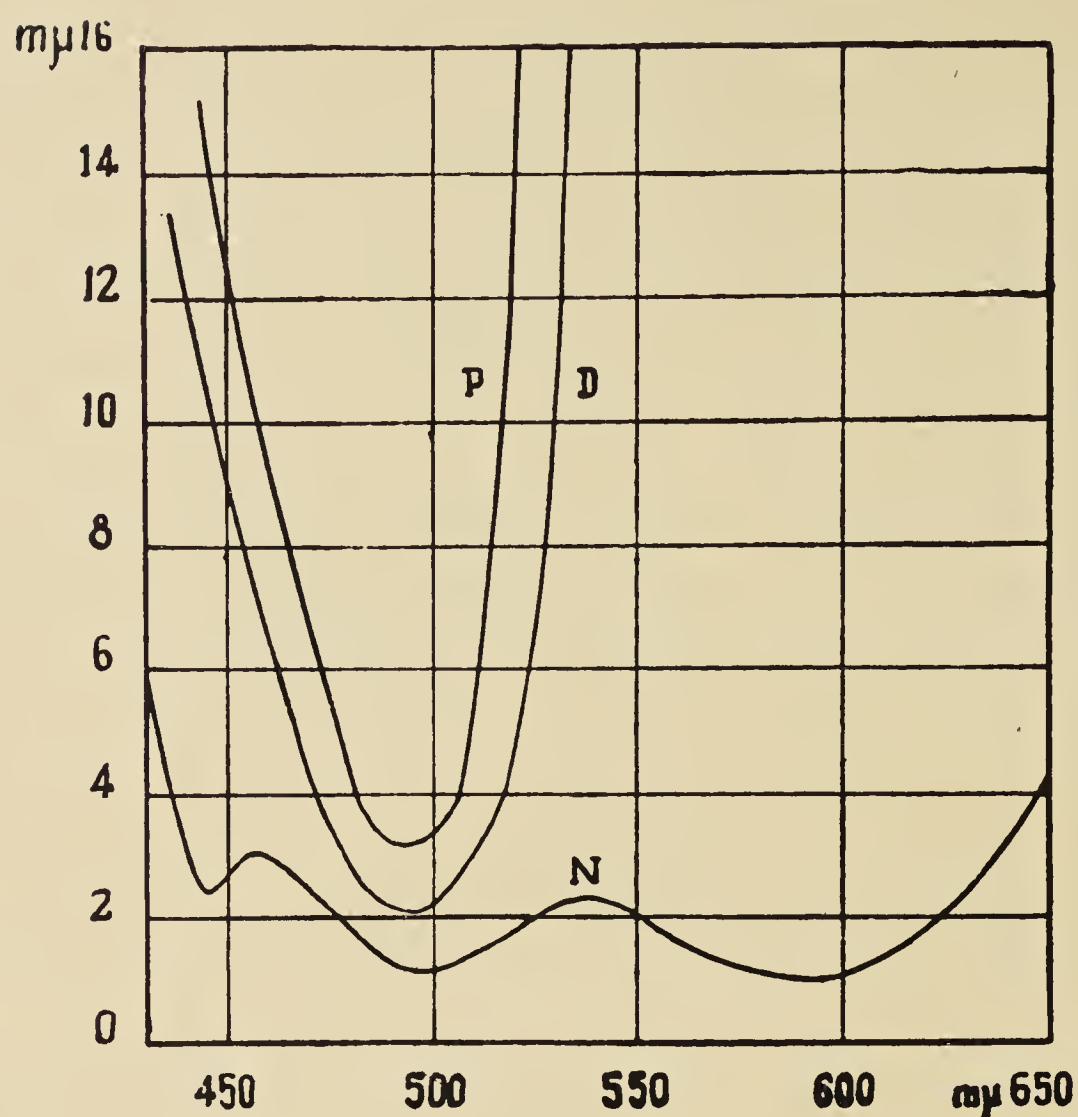


Figure 2. Comparison of hue discrimination curves for protanopic (P), deuteranopic (D) and normal vision (N).

point in the spectrum where the colour as perceived by the protanope changes most rapidly. The features of the hue discrimination curve observed at greater wavelengths would, however, disappear and be replaced by a continuous falling off in the rate of change of observable colour with wavelength. The features of protanopic vision thus deduced are in agreement with those actually observed. The comparisons between normal and protanopic vision in respect of spectral luminosity and hue discrimination exhibited respectively in figures 1 and 2 are based on the observations of F.H.G. Pitt.

We now proceed to discuss the characteristics of protanomalous vision on the assumption that this type of vision results from a replacement of the ferroheme which alone is present in protanopic vision by a small proportion of ferriheme. The effect of such replacement on vision would be principally felt in the region of wavelengths where the absorption of ferriheme is comparable with or actually stronger than that of the ferroheme. This is the region between 560 and 650 $m\mu$ where in normal colour vision, green changes over to yellow and then to orange and red. In this region, the protanomalous observer would see hues not perceived by the protanope, and recognise that they alter with the location in the spectrum. In other words, besides the rapid change in colour around 495 $m\mu$ which is apparent alike to the normal observer and the protanope, the protanomalous

observer would observe colour changes roughly analogous to those apparent to normal vision in the region of wavelengths between 560 and 650 $m\mu$, but of a much less precisely defined character. The greater the quantity of ferriheme which replaces ferroheme, the more clearly would these features be perceived. It may therefore be expected that the protanomalous vision would exhibit in its hue discrimination curves a wide range of variation, approximating to normal colour vision at one end of the range to that of protanopic vision at the other end.

The conclusions reached above find support in the experimental data represented in figure 3 below of the hue discrimination curves of four protanomalous observers and one normal observer which have been selected from the extensive set of data presented in a paper by McKeon and Wright.

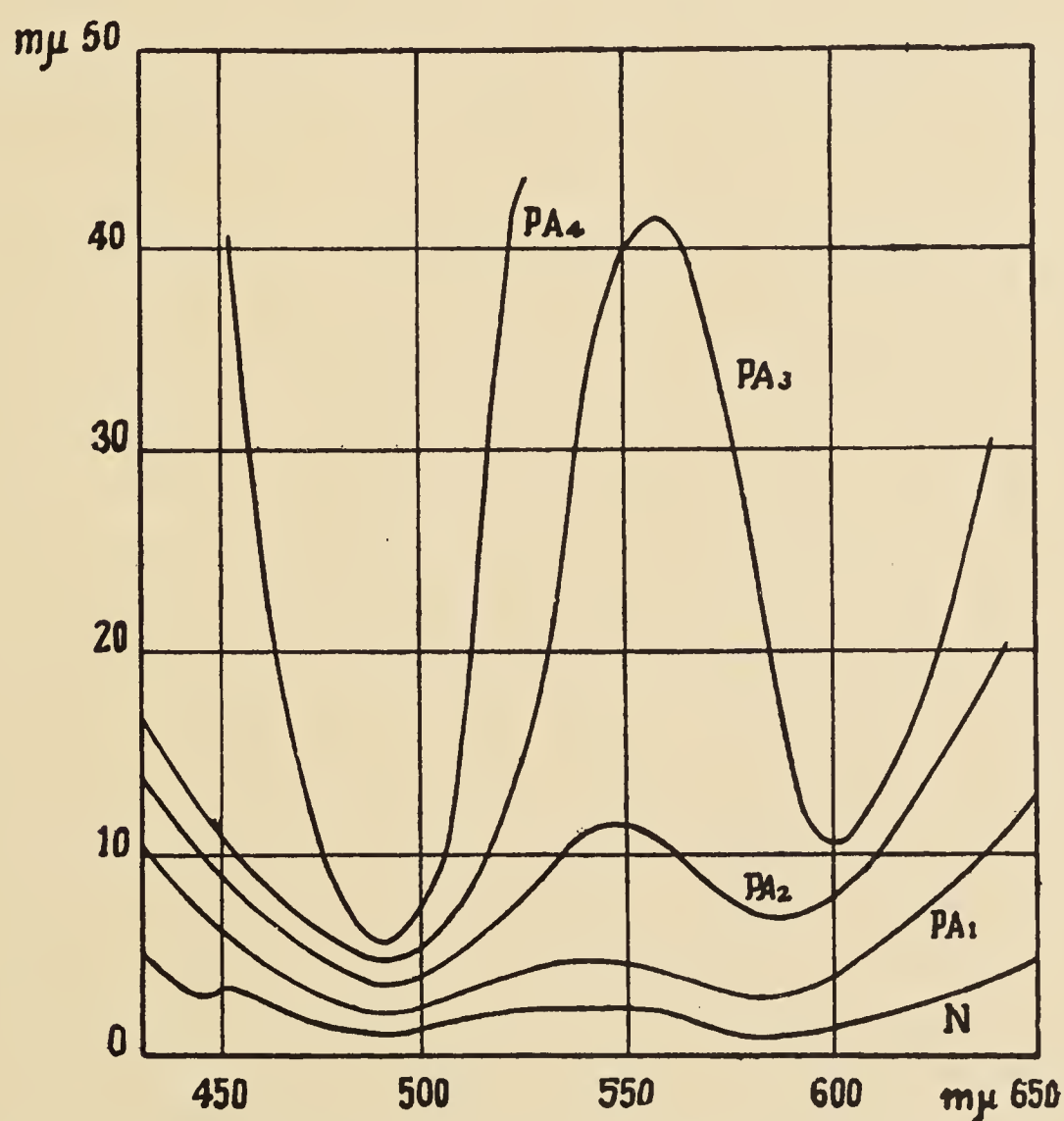


Figure 3. Comparison of hue discrimination curves of protanomalous (Pa) and normal observers (N).

4. Deuteranopic and deuteranomalous vision

A biochemical situation which results in the presence of an excess of ferriheme over ferroheme would have consequences in respect of colour vision which can readily be foreseen. As the ferroheme-ferriheme ratio diminishes, the region of wavelengths in the spectrum within which the absorptions of the two pigments

are of comparable strength would shift towards shorter wavelengths and their overlap would extend and become effective until it completely covers the sector of the spectrum which appears green to a normal observer. In other words, the green and red sectors of the spectrum cease to have a separate existence and merge to form a tract in which the yellow and orange regions which ordinarily form only a fringe between them extend and cover the entire range of wavelengths referred to. Thus, instead of the normal colour sequence of green, yellow, orange and red, a band of colour would appear which may be described as yellow with a greenish tinge at one end and a reddish tinge at the other. This would cover the entire region where the absorption spectra of ferroheme and ferriheme co-operate. It would terminate at about $495\text{ m}\mu$ where the blue-violet sector of the spectrum begins. Thus, again, as in protanopic vision, the spectrum consists of only two sectors meeting at about that wavelength. The difference between deuteranopic and protanopic vision is that in the former case, the spectrum goes up to the extreme red end instead of stopping off at shorter wavelengths. The colours observed would also be different in the two cases.

Observational evidence confirming the correctness of the foregoing explanation of deuteranopic colour vision is furnished by the spectral luminosity curves and the hue-discrimination data for several deuteranopic subjects which have been made available by the work of F.H.G. Pitt. These have been represented alongside of those of protanopic and normal observers in figures 1 and 2 above respectively in the text. They show very clearly the much greater extension of the spectral luminosity curves towards the red in deuteranopic as compared with protanopic vision. The difference between deuteranopic and normal vision in respect of the spectral luminosity curves is also distinctly shown. The hue discrimination curves, on the other hand, show a general similarity between protanopic and deuteranopic vision and a striking dissimilarity with the normal vision. The observations, however, reveal the noteworthy and significant fact that deuteranopic vision has a distinctly better hue discrimination than protanopic vision in the wavelength range between 400 and $530\text{ m}\mu$. But hue discrimination is completely lacking in the region of greater wavelengths in both types of vision.

We shall not here pause to discuss the results of colour mixing experiments made with observers having one or the other of these two types of defective vision, as also studies of the colour confusions which they exhibit when presented with test objects which appear of different hue to normal observers. These features of protanopic and deuteranopic vision are readily deducible from the fundamental results set forth above. We shall proceed to consider the features of deuteranomalous vision which are of special interest if only for the reason that this type of defective vision outnumbers all the other types put together. Deuteranomalous vision can be distinguished from normal vision by the method of observation by which its existence as well as that of protanomalous vision was discovered, viz., that of requiring the person tested to match a monochromatic yellow by a mixture of monochromatic green and red radiations by varying their relative

intensities. A protanomalous observer would require a smaller ratio of green to red than is required for normal vision, while a deuteranomalous observer would need a larger ratio. This is a clear indication that red light appears dimmer in protanomalous than in normal vision, while it appears brighter in deuteranomalous vision. Since protanomaly is explicable as a consequence of the ferroheme-ferriheme ratio being larger than the normal, it may be inferred that deuteranomaly is a result of ferriheme being present in the retina in excess of that required for normal colour vision.

The observable consequences of ferriheme being present in a proportion greater than normal should be of three kinds: (a) a shift of the spectral luminosity curves towards longer wavelengths as compared with normal; (b) a reduction in the power of hue discrimination at all wavelengths greater than 5000 Å and (c) changes of the chromatic coefficients, viz., the intensity ratio between green and red monochromatic radiations of chosen wavelengths which when superposed would match the colours of the spectrum at various wavelengths. In respect of all these features, it may be expected that the magnitude of the observed changes would depend upon the actual proportion of ferriheme present. The more nearly the ferroheme-ferriheme ratio approaches normal, the greater would be the resemblance between deuteranomalous and normal vision. *Per contra*, the greater the excess of ferriheme present, the more would deuteranomalous vision tend to approach deuteranopic vision in its characters.

The observational evidence available supports the foregoing inferences. D B Judd in a published report has drawn the individual spectral luminosity curves of twelve protanomalous and of six deuteranomalous observers and compared them respectively with the averages of the luminosity curves of six protanopes and of six deuteranopes. As is to be expected, the luminosity curves of both the protanomalous and of deuteranomalous observers exhibit a certain spread amongst themselves. The significant result emerges that the average curve for the six deuteranopes appears clearly separated and shifted towards longer wavelengths from the region where the individual curves of the deuteranomalous observers are recorded.

The fall in power of hue discrimination and the alterations of the chromatic coefficients are necessarily related to each other. For, the extension of the overlap of the absorption spectra of ferroheme and ferriheme due to the latter being present in excess would obliterate the colour difference between the green and the red sectors of the spectrum. This, on the one hand, would result in a large increase in the limen for hue discrimination and also shift the wavelength where the minimum of limen appears towards the red where there is no such overlap. Simultaneously, the chromatic coefficients for green and red would tend to approach and become equal to each other in the same region where the power of hue discrimination registers a large diminution.

The foregoing inferences find very clear support in the data represented in figure 4 where the chromatic coefficients and the hue discrimination curves for

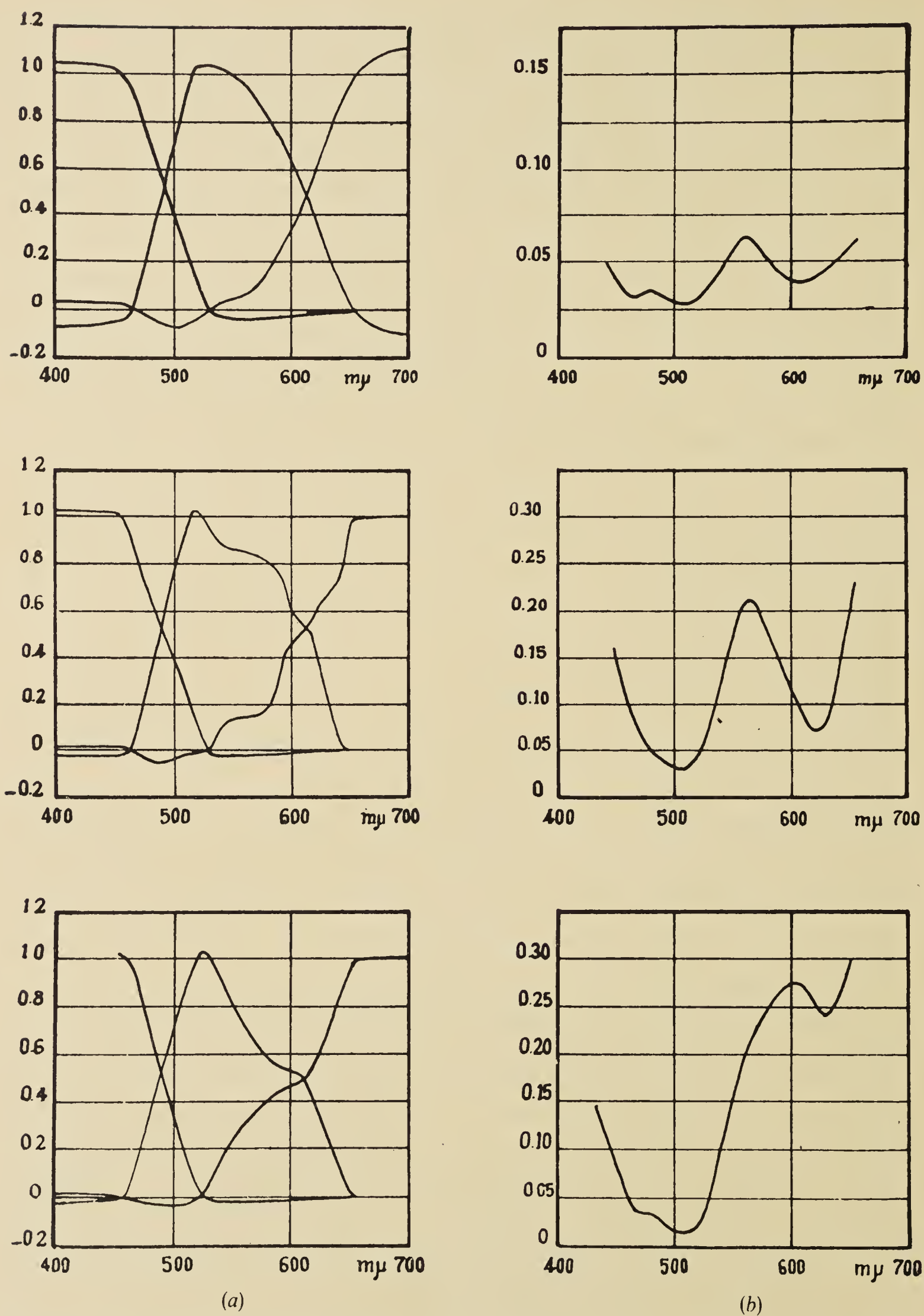


Figure 4. (a) Spectral chromaticity coefficients and (b) hue discrimination curves of three deuteranomalous observers according to J H Nelson. The unit of the ordinates in (b) is 100 $m\mu$.

three different deuteranomalous observers are shown side by side to exhibit the correlations between them. These have been selected from a more extensive set of observational data published by J H Nelson.

5. Tritanopia

It has been shown in the third part of this memoir that the carotenoid pigment xanthophyll is the visual receptor in the blue and violet regions of the spectrum. Its absorption which is negligible at wavelengths greater than $520\text{ m}\mu$, rises very steeply around $490\text{ m}\mu$ and after reaching fairly high values between 480 and $440\text{ m}\mu$ drops down again to relatively small values in the far violet.

It follows from what has been stated that if xanthophyll is totally absent from the retina, colour vision would be seriously affected in the blue-violet sector. In the first place, the observer would be unable to distinguish between the blue and green colours in the spectrum. The luminous efficiency would fall off towards the end of the spectrum rather more rapidly than it would for a normal observer. The hue discrimination curve should also show striking abnormalities. While the usual well-marked minimum of the limen around $590\text{ m}\mu$ would continue to be observed, the form of the curve in the green and blue regions would be totally different. The maximum value of the limen observed around $540\text{ m}\mu$ and the minimum around $490\text{ m}\mu$ would both disappear. Instead, there should be a progressive increase in the limen with diminishing wavelength at all wavelengths less than $590\text{ m}\mu$.

Though tritanopia is usually regarded as a rare condition, a search initiated by W D Wright involving the extensive publication of test colour charts resulted in a fairly large number of cases being discovered and investigated. The incidence of tritanopia has been found to be of the order of 1 in 20,000 persons. The indications are that tritanopia is an inherited condition but its incidence amongst women and men is not so widely different as in the cases of the more commonly observed types of defective vision. The consequences of the absence of xanthophyll in the retina indicated above are in general agreement with the findings of W D Wright. It was, however, noticed that while the power of hue discrimination virtually disappears in the blue-green wavelengths, it shows a rather surprising recovery near the far-violet end of the spectrum. This would seem to suggest that in the spectral region where the absorption of xanthophyll becomes very small, the other visual pigments ferroheme and ferriheme, play a not wholly negligible part in colour vision and colour discrimination.

The perception of light and colour and the physiology of vision—Part VII. General summary

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1. Observations of the retina

A simple but extremely powerful technique has been devised which enables an observer without any instrumental aid to see his own retina and study its functioning in varied circumstances. The observations made by this method have enabled important conclusions to be arrived at regarding the constitution of the retina and the mechanism by which light and colour are perceived. The observer sits facing a brightly lit white screen and views it through an appropriate colour filter held in front of his eye. After a sufficient interval of time, he fixes his vision on some particular point on the screen and then removes the filter. An enormously magnified picture of the retina then appears on the screen, the nature of which depends very much on the particular colour filter used. The explanation of the phenomenon is that the rays of the spectrum which is the first instance are absorbed by the filter, suddenly impinge on the retina when the filter is removed, and excite localised sensations over its different areas. These sensations project themselves on the observing screen as an enlarged image of the retina.

By correlating the absorption spectra of the filters used with the pictures of the retina perceived by the observer, it has been ascertained that the retina contains three visual pigments whose absorption spectra lie in different regions of the spectrum: Pigment A has an absorption lying in the spectral range 4000 to 5000 Å. Pigment B exerts an extremely powerful absorption in the wavelength range between 5000 and 6000 Å, while pigment C exerts a moderately powerful absorption in the region from 6000 to 7000 Å, but its absorption also extends into and partly overlaps the region covered by pigment B.

2. The role of the visual pigments

The nature and properties of light when correlated with the observed facts concerning the perception of light and colour enable us to determine the role

played by the visual pigments in the retina. Each different monochromatic light in the spectrum represents radiation characterised by a different energy-quantum; the magnitude of the quantum increases progressively from the red to the violet end of the spectrum. It is a fact also that the colours observed in the spectrum change progressively and continuously from one end of it to the other. Some 250 different colours can be perceived over the whole range. A change of only one half of 1% in the magnitude of the light-quantum incident on and absorbed by the retinal pigments is usually sufficient to make an observable change of perceived colour, while in some parts of the spectrum a much smaller difference is thus detectable.

Monochromatic radiation is the fundamental entity with which the physicist is concerned in optics and spectroscopy. It follows from what has been stated that the fundamental visual sensations are also those excited by monochromatic radiation. The observed precision of colour perception would be inexplicable except on the hypothesis that the function of the visual pigments in the retina is to receive, absorb and then to pass on the absorbed energy-quanta to the central parts of the visual mechanism without any addition or subtraction, themselves returning to their original energy-states.

3. Identification of the visual pigments

The identification of the visual pigments presents no particular difficulties. In day-light vision, there is a highly pronounced maximum of luminosity in the spectrum at about 5600 Å, on either side of which the brightness falls off rapidly. It follows that pigment B of which the absorption lies in the green plays the major role in human vision, a role somewhat analogous to that which the absorption in the red by chlorophyll plays in the photosynthesis by green leaves. We can, therefore, unhesitatingly identify our pigment B with ferroheme which exhibits a powerful absorption of light in the green sector located at the same position as the maximum of visual luminosity in the spectrum.

Oxidation-reduction mechanisms play a fundamental role in the chemistry of the living structures of aerobic organisms. The recognition of ferroheme as the principal visual pigment thus automatically involves the identification of pigment C which appears in the retina in close association with pigment B as ferriheme. It is known that the absorption of light by ferriheme is weaker than that of ferroheme, but extends much further towards longer wavelengths and is indeed sensible up to the extreme red end of the spectrum. These are the properties needed for the visual pigment which functions in that region.

The pigment A which absorbs light between 4000 and 5000 Å and is the mediator of vision in the blue and violet sectors of the spectrum can be none other than the carotenoid pigment xanthophyll which gives the characteristic golden yellow colour to the yolk of the common hen's egg. Xanthophyll finds its way into

the human body through the consumption of food products containing it, and its presence in the retina is therefore not a matter for surprise. Indeed, it is the same yellow pigment which led to the anatomical name of *macula lutea* being given to the physiologically most important area in the retina.

4. Colour and luminosity in the spectrum

The known features of the absorption spectra of the visual pigments enable a satisfactory explanation to be given of the distinctive features noticeable in the different sectors of the spectrum. The very steep rise in the absorption by xanthophyll which appears in the wavelength range around 4900 \AA is responsible for the rapid change in the colour of the spectrum from green to blue and the very low value of the limen of wavelength alteration needed for observable change of colour appearing in that region. The similar but less striking fall of the limen in the region around 4400 \AA where the colour of the spectrum changes from blue to violet is likewise attributable to the rapid fall of the absorption by xanthophyll with diminishing wavelength appearing in that region.

The overlap in the absorption spectra of ferroheme and ferriheme between 625 and $566 \text{ m}\mu$ gives rise to the appearance of yellow and orange in the spectrum as an interpolation between the green and red sectors, the yellow where the absorptions of the two pigments are of comparable strength, and the orange where the absorption by ferriheme is stronger than by ferroheme. The steep fall in the absorption by ferroheme in the same region is responsible for the limen of wavelength change needed for an observable difference of colour reaching very low values in the region around $590 \text{ m}\mu$.

The progressive fall in the luminosity of the spectrum and the increasing limen of wavelength change for a perceptible colour difference manifested near the extreme violet and red ends of the spectrum appear as consequences respectively of the diminishing absorption and the diminishing slope of the absorption curves of xanthophyll and of ferriheme in those two regions.

Some remarkable effects are observed when a colour filter which transmits only the blue-violet part of the spectrum is held in front of the eye and a polaroid is placed and alternately taken out and put in before the filter. These effects cease to be observable when the illumination of the field under observation is diminished so as to fall below the photopic level. They afford a conclusive demonstration that xanthophyll is the visual pigment which enables us to perceive the blue and violet colours of the spectrum.

5. Non-homogeneous light

The visual sensations produced by heterogeneous light result from the synthesis by the centre of the sensations excited by the monochromatic radiations of which

it is composed. The results of the synthesis may be either a chromatic or an achromatic sensation. Chromatic sensations arise when only two of the three visual pigments function, as for example when the radiations from the extreme red and violet ends of the spectrum are superposed, giving rise to the purples, or when the superposed radiations lie in the spectral range where xanthophyll has no absorption, viz., in the red and green sectors; the resultant sensation is then a pure spectral colour.

The achromatic sensation arises when all the three visual pigments function in appropriate strengths. This enables a satisfactory explanation to be given of the fact that in a whole series of cases, the superposition of only two monochromatic radiations of appropriately chosen wavelengths results in the complete abolition of colour. In general, the sensations excited by heterogeneous light are a mixture of the chromatic and achromatic sensations which may be regarded as independent effects. The fact that all observable colours may be regarded as a superposition in appropriate proportions of white light and a pure spectral colour (including the pure purples) thus receives a satisfactory explanation.

The results obtained in experiments in which a pure spectral colour is sought to be reproduced by the superposition of other spectral colours may be interpreted in the same manner. The so-called spectral chromaticity coefficients determined in such experiments, when they have positive values, exhibit a parallelism with the absorption strength of the visual pigments which function in the respective spectral regions. *Per contra*, the appearance of negative values of the coefficients indicates that achromatic sensations are produced.

6. Defective colour vision

The existence of both ferroheme and ferriheme as visual pigments in the retina presupposes that there is a biochemical mechanism which determines the proportions in which they are normally present. Any deviations of the mechanism from normality would result in ferriheme being either totally absent or else being present much in excess. There would also be intermediate cases. The existence of four types of inheritable defect in colour vision would thus be explicable in terms of the biochemical mechanism which determines the ferroheme-ferriheme ratio in the retina. These are respectively the protanopic, protanomalous, deuteranomalous and deuteranopic types of colour vision. The features of these different types of defects are readily predictable and the results thus deduced are in agreement with the observed facts. Tritanopia is likewise explicable as due to the complete absence of xanthophyll from the retina.

7. References

The literature on colour vision and related topics is very voluminous. The under-mentioned books were found very useful by the writer. Besides containing extensive bibliographies, they gave clear

accounts of the present state of knowledge in their respective fields and factual information of value:

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The role of the retina in vision

SIR C V RAMAN

1. Introduction

Our sense-organs are the gateways through which a knowledge of the external world reaches us. The relationships which exist between our sensory impressions and the nature of the stimuli which excite those impressions are thus matters of great importance. For, they furnish us with indications regarding the processes by which the stimuli received by the sense-organs are transformed into sense-impressions. Studies on the perception of stimuli of the simplest character are particularly important, since their results are most readily analysed and understood.

Light which appears as a sharply-defined line in the spectrum is the simplest type of radiation. It is appropriate therefore that we recognise the sensations excited by monochromatic lights of various colours as the primary or fundamental visual sensations. Likewise, when a continuous spectrum of radiation is dispersed by a prism into a band of colour, each strip which the eye can distinguish as being different in hue from the strips on either side can be regarded as a primary or fundamental visual sensation. Hence the primary visual sensations are as numerous as the hues which can be distinguished from each other in the spectrum by the eye under the most favourable conditions of observation.

We may here usefully recall various facts of observation. It is known that as many as 250 different hues in the spectrum can be distinguished under appropriate conditions. The spectral shift which results in an observable change of hue is less than 20 \AA over the greater part of the spectrum and as little as 10 \AA in some parts. It is also known that the addition of white light in any desired proportion to a pure spectral colour does not change the observed hue. Quantitative studies have further established that the power of the eye to discriminate between the hues of adjacent regions in the spectrum is not sensibly diminished even when the colours are diluted by considerable additions of white light to the fields under comparison.

The facts of experience stated above are just what we would expect to find if the colours of homogeneous light are the primary or fundamental colour sensations. That such a relationship exists is not in the least surprising. For, our organs of vision would be of little use to us, if the external stimuli and the sensations which

they excite are not very simply related to each other. We are, therefore, entirely justified in concluding that the basic or primary sensations with which physiological optics has to concern itself are those produced by the radiations which are recognised by the physicist as simple and homogeneous. These sensations stand in a category by themselves and they are clearly distinguishable from the sensations excited by compound or heterogeneous radiation.

The basic problem in physiological optics is thus to find an answer to the question, how does the apparatus of human vision function and enable us to distinguish the colours of monochromatic lights from each other with the degree of precision actually observed?

2. The nature of the visual process

Geometrical optics and the wave-theory of light form an appropriate basis for a consideration of the propagation of light in refractive media. Thus, they enter into the realm of physiological optics when we consider the functioning of the cornea and the crystalline lens and the formation of images of external objects on the retina. But when we reach the retina, wave-optics ceases to be relevant, and Einstein's concept of light as consisting of discrete energy-quanta or photons necessarily takes its place. For, the wave-theory is incapable of giving any acceptable explanation of such phenomena as the emission or absorption of light and the transformations of light-energy. Hence, we must lay aside the ideas and language of the wave-theory and think of light as a stream of photons, if we are to make any progress towards an understanding of the facts of human vision.

Homogeneous light may be described as a stream of radiant energy consisting of units or quanta which are all identical. The quanta increase progressively in magnitude as we move up the spectrum from the red towards the violet end. The colour of the perceived light also changes progressively in the same circumstances. We are, therefore, justified in associating the sensation of colour experienced in homogeneous light with the energy carried by the individual photons or light-quanta. The other sensation excited by light, viz., its luminosity, is determined by the number of photons traversing any given area per unit of time. Thus, the two physiologically experienced sensations of colour and luminosity excited by homogeneous light are connected respectively with the two specifiable properties of the radiation in the language of the quantum theory.

A fuller insight into the nature of the visual process is furnished by quantitative data of two different sorts which are available regarding the sensations excited by homogeneous light. These data are represented in the form of the curves known respectively as "the luminous-efficiency curve" and "the hue-discrimination curve" of the visible spectrum. The luminous-efficiency curve exhibits the results of a comparison of the visual luminosity of the different parts of the visible spectrum for a constant energy-flux. The hue-discrimination curve represents

determinations of the smallest difference of spectral position necessary to give an observable difference in colour between two fields of illumination, the luminosities of which are equal.

The data of observation represented in the hue-discrimination curve are particularly significant. In the entire range of the visible spectrum, a change in the energy of the photon of 1% is sufficient to give a perceptible change of colour. Indeed, this statement underestimates the power of the visual mechanism to perceive differences of colour. Except near the ends of the spectrum where the luminosity is low, a change of one-half of 1% in the energy of the photon is everywhere detectable. In the blue-green region, a change of one-fifth of 1% and in the orange-yellow, of one-sixth of 1% reveals itself by an alteration of the observed colour.

The facts of experience stated above are most readily understood if vision is assumed to result from the acceptance of the energy of the photon by the retina and its immediate transference without addition or subtraction to the centres of perception. We do not have to assume that all the photons incident on the retina are thus dealt with. A considerable proportion, especially in daylight vision, may be expected merely to pass through the retina and suffer absorption by the pigmented choroid coat behind it. The energy of the other photons may be expected to be used up in producing thermal effects or photochemical changes in the substance of the retina. The photons thus disposed of cannot be effective in vision. The observed precision of the colour sense over the entire visible spectrum precludes any such possibility.

The distribution of visible luminosity in the continuous spectrum of radiation emitted by a hot body differs greatly from the distribution of energy in it. This difference is a characteristic property of human vision and arises from the enormous differences between the luminous efficiencies of homogeneous radiation in the different parts of the spectrum. The efficiency exhibits a pronounced maximum in the green and falls off rapidly as we proceed away from it either towards the red or towards the violet end of the spectrum, but more rapidly so in the latter case. Indeed, the luminosity of the violet end of the spectrum is very low. These differences in the ability of photons of different energies to excite the sensation of luminosity are ascribable to the differences in the probability of their energies being taken over by the retina and transmitted to the centres of perception as indicated above. On this basis, we should expect to find noticeable relationships between the variations of luminosity and of colour in the different parts of the spectrum, and this is actually the case. We shall return to these topics later.

3. The spectral sensitivity of the retina

A technique of observation has been devised and used by the author which is both simple and effective and which enables an observer to see a greatly enlarged

picture of his own retina in the act of functioning. The technique enables highly important information regarding the structure of the retina and its sensitivity to light in different areas and in different parts of the spectrum to be obtained.

We may first briefly explain the technique and how it works. By screening the eye from an external illumination for a short period which need not exceed a few minutes, it is possible greatly to increase the sensitivity of the retina to light. This improvement may be made spectrally selective, in other words, restricted to any desired part of the spectrum by using an appropriately chosen colour filter and holding it before the eye for a suitable interval of time. Accordingly, when the filter is removed and a brightly lit white surface is viewed by the observer, he sees on it a picture of his own retina which exhibits the selective responses of its different areas to the parts of the spectrum which had been screened off by the filter before its removal. This picture, of course, is fugitive. But it may be recalled as often as desired by putting back the filter and then removing it from before the eye.

A series of ten drawings of the retina showing the effects observed with different colour-filters in the manner explained above are reproduced in the accompanying colour plates. The colour-filters were prepared by dyeing gelatine films on glass with different water-soluble dyes to an appropriate depth of colour and then washing and drying the film. The commercial names of the colouring matters used are entered against each figure. We shall proceed to comment briefly on the effects noticed with the different filters.

It is significant that a rhodamine filter, which cuts off the green sector of the spectrum without weakening other regions, gives no observable effect following its removal. This indicates that the sensitivity of the retina to the green which is the most luminous part of the spectrum is not sensibly enhanced by its being screened off from the eye for a brief period.

Very striking and beautiful effects are observed using a filter dyed with methyl-violet. The density of the filter and the accompanying changes in the strength of the absorption and the extent of cut-off in the spectrum greatly influence the observed results. In all cases, the foveal area and the foveolar depression are conspicuous features, the colour which they exhibit varying with the density of the filter. A lightly-dyed filter cuts off the yellow and orange sectors and weakens the green of the spectrum. With such a filter, the foveal region appears green, while yellow and orange are the dominant colours elsewhere in the field. A halo of orange-red hue appears encircling the foveal disc (figure 1 in the colour plate).

Using filters whose absorption is at the violet end of the spectrum and which accordingly appear yellow or orange by transmitted light, the retina exhibits a blue glow following the removal of the filter (figure 9 in the colour plate). With filters which cut off the red of the spectrum and allow the rest to pass through freely, a rose-red glow appears covering the entire field following the removal of the filter (figure 3 in the colour plate). The fovea is either not seen at all or is only very dimly visible in the retinal picture in these cases. Filters which appear green

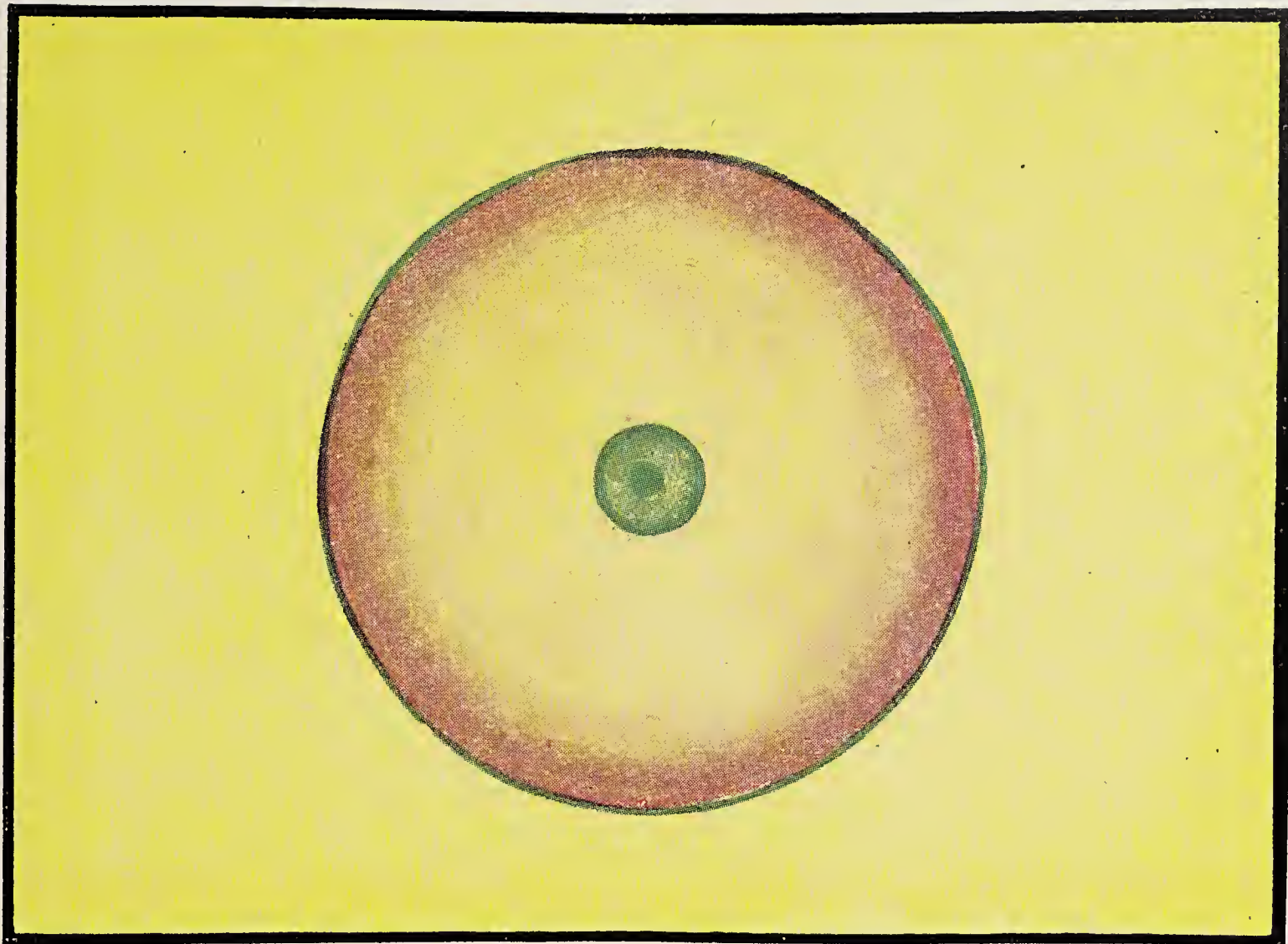


Figure 1. Picture of retina seen by methyl violet filter.

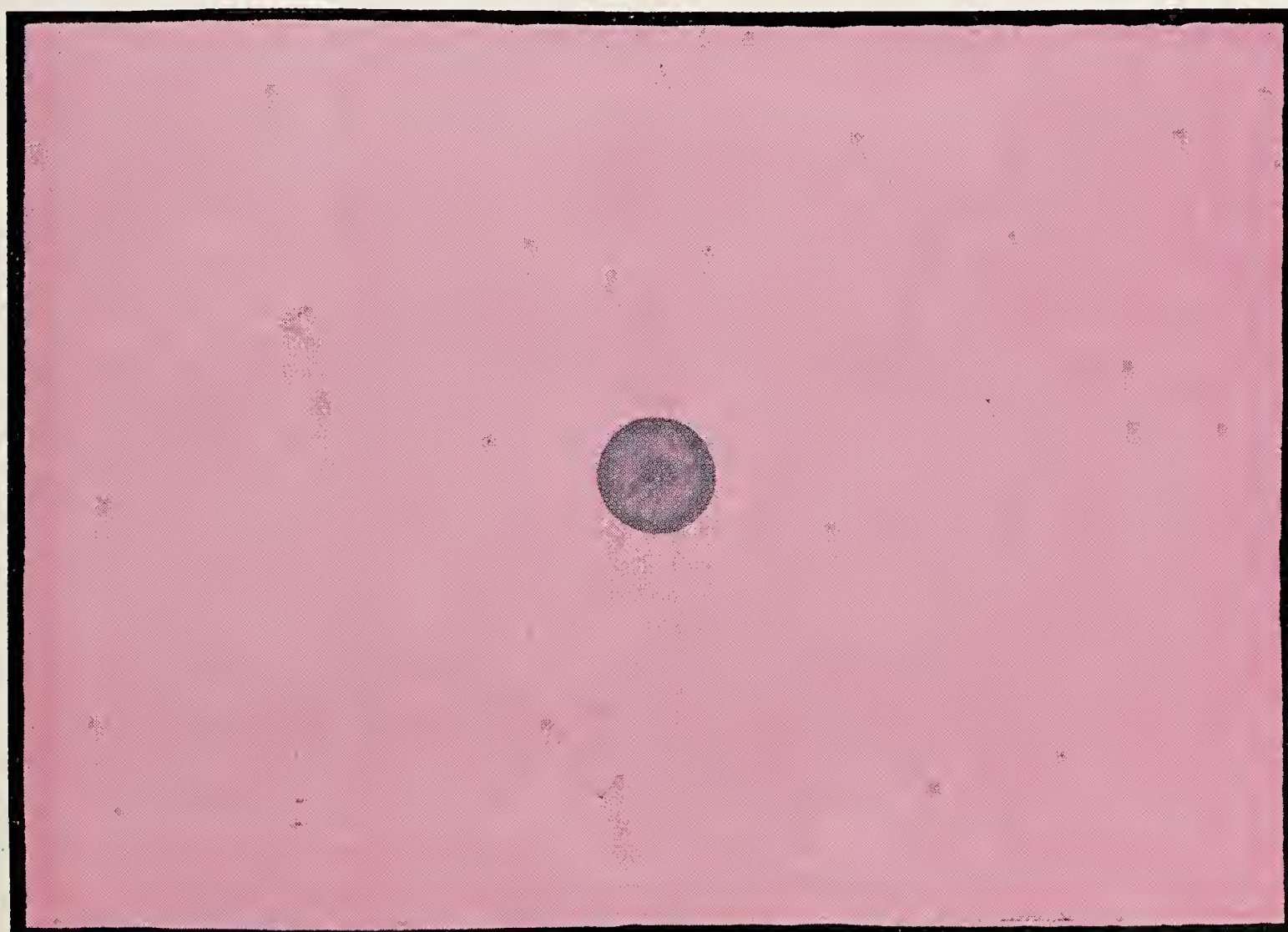


Figure 2. Picture of retina seen by coomassie brilliant blue filter.



Figure 3. Picture of retina seen by light lissamine green filter.

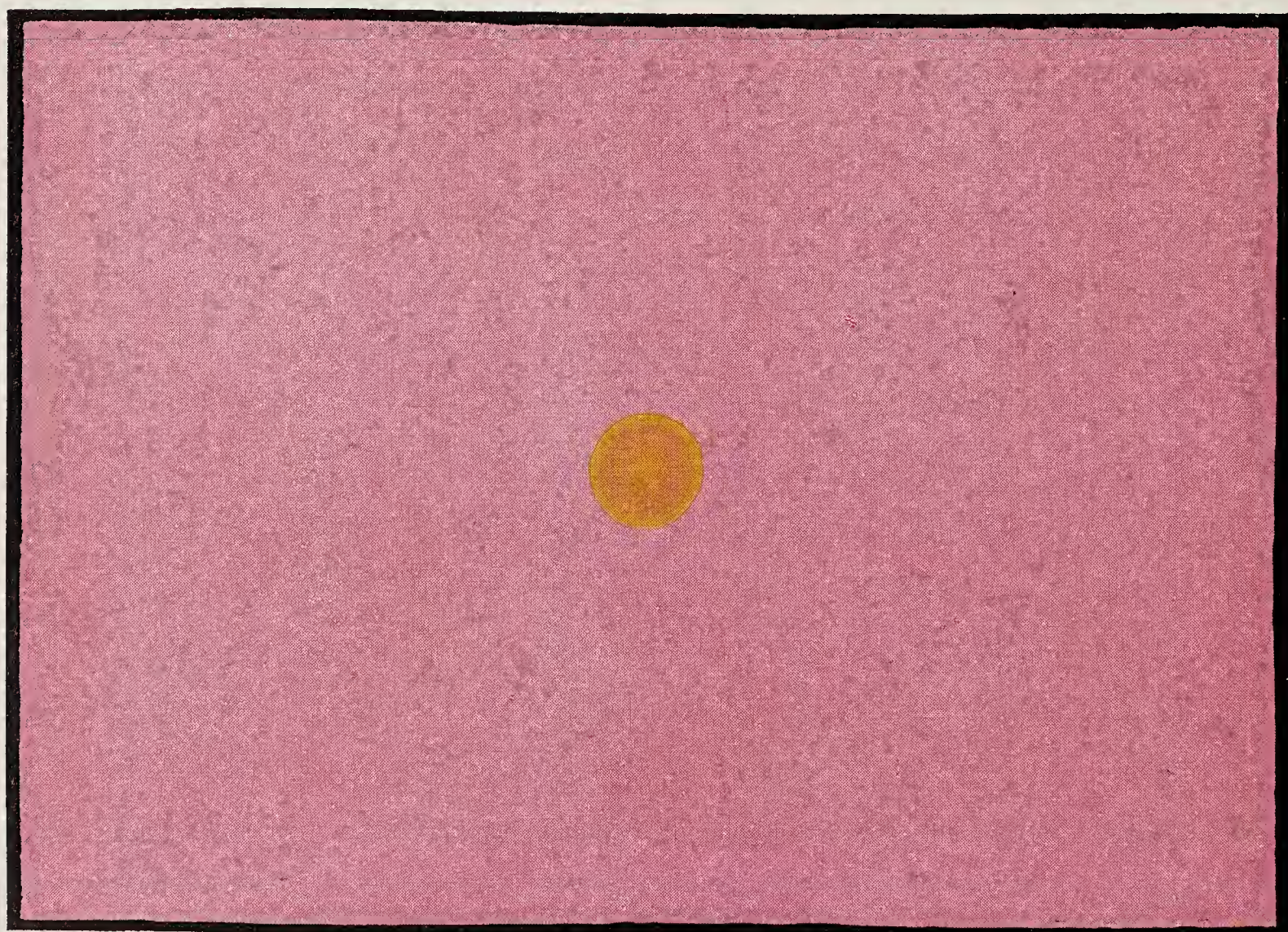


Figure 4. Nickel chloride.

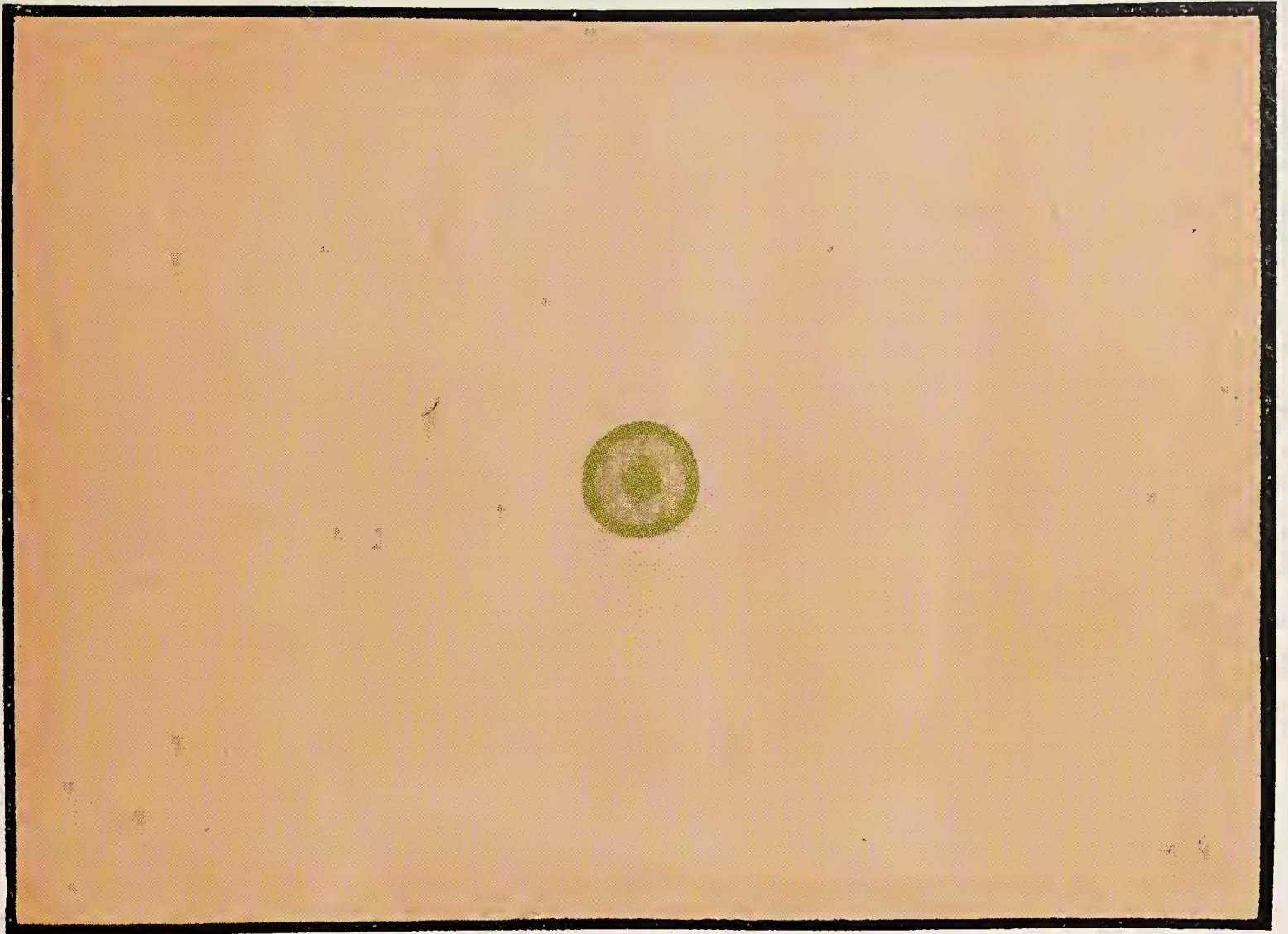


Figure 5. Picture of retina seen by coomassie navy blue filter.

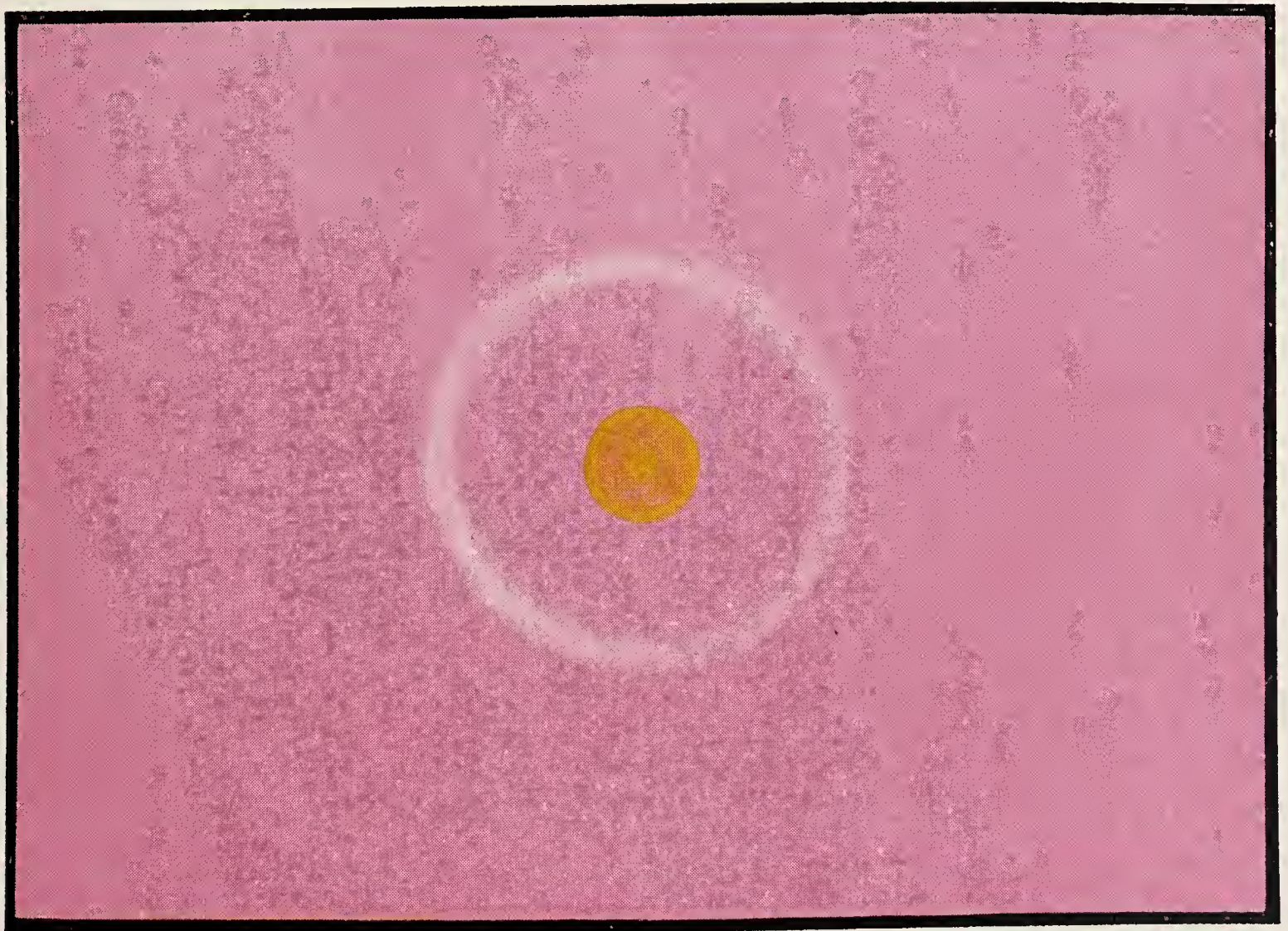


Figure 6. Picture of retina seen by deep lissamine green filter.

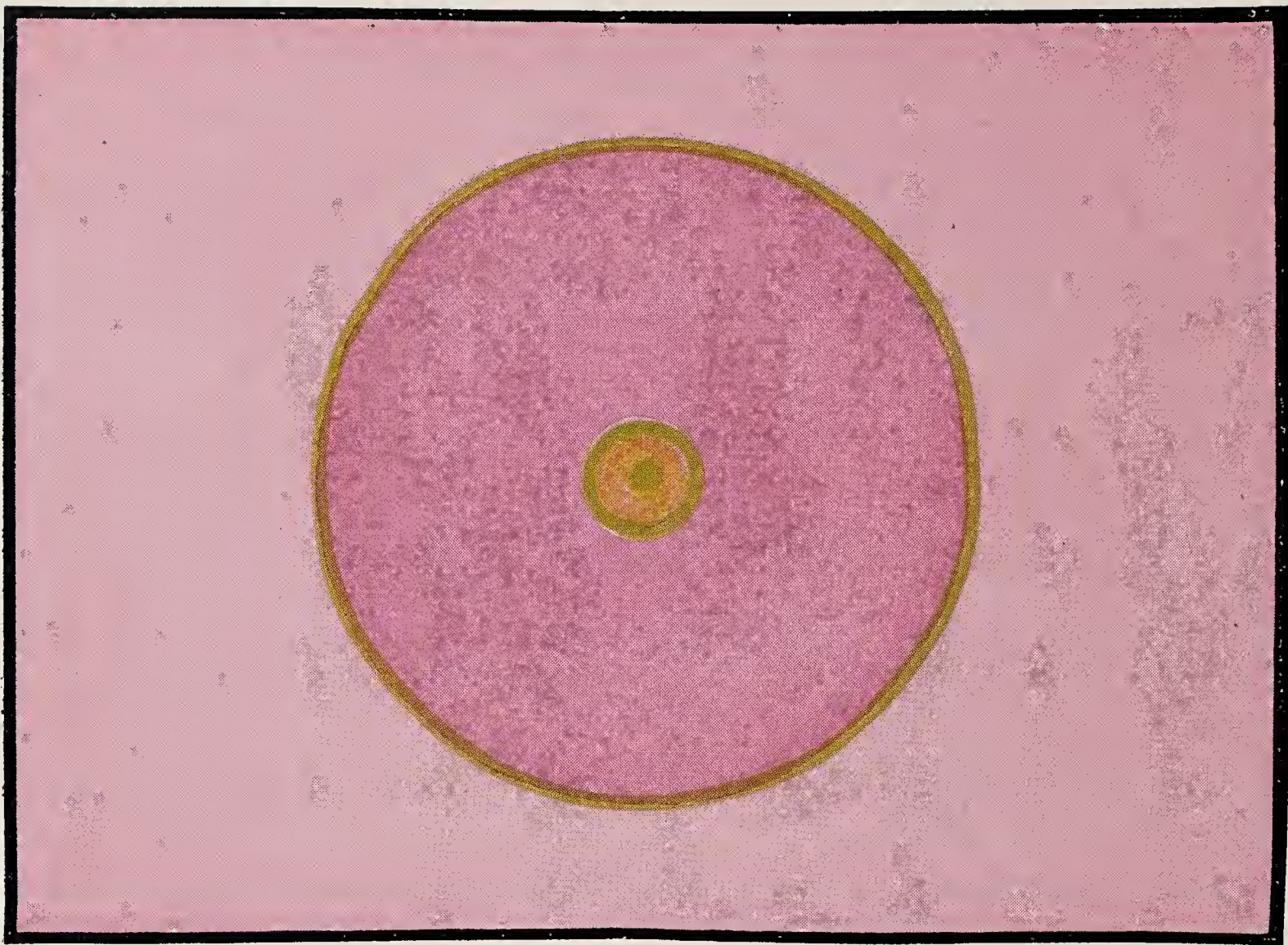


Figure 7. Picture of retina seen by deep blue filter.



Figure 8. Picture of retina seen by greenish blue filter.



Figure 9. Picture of retina seen by deep orange filter.

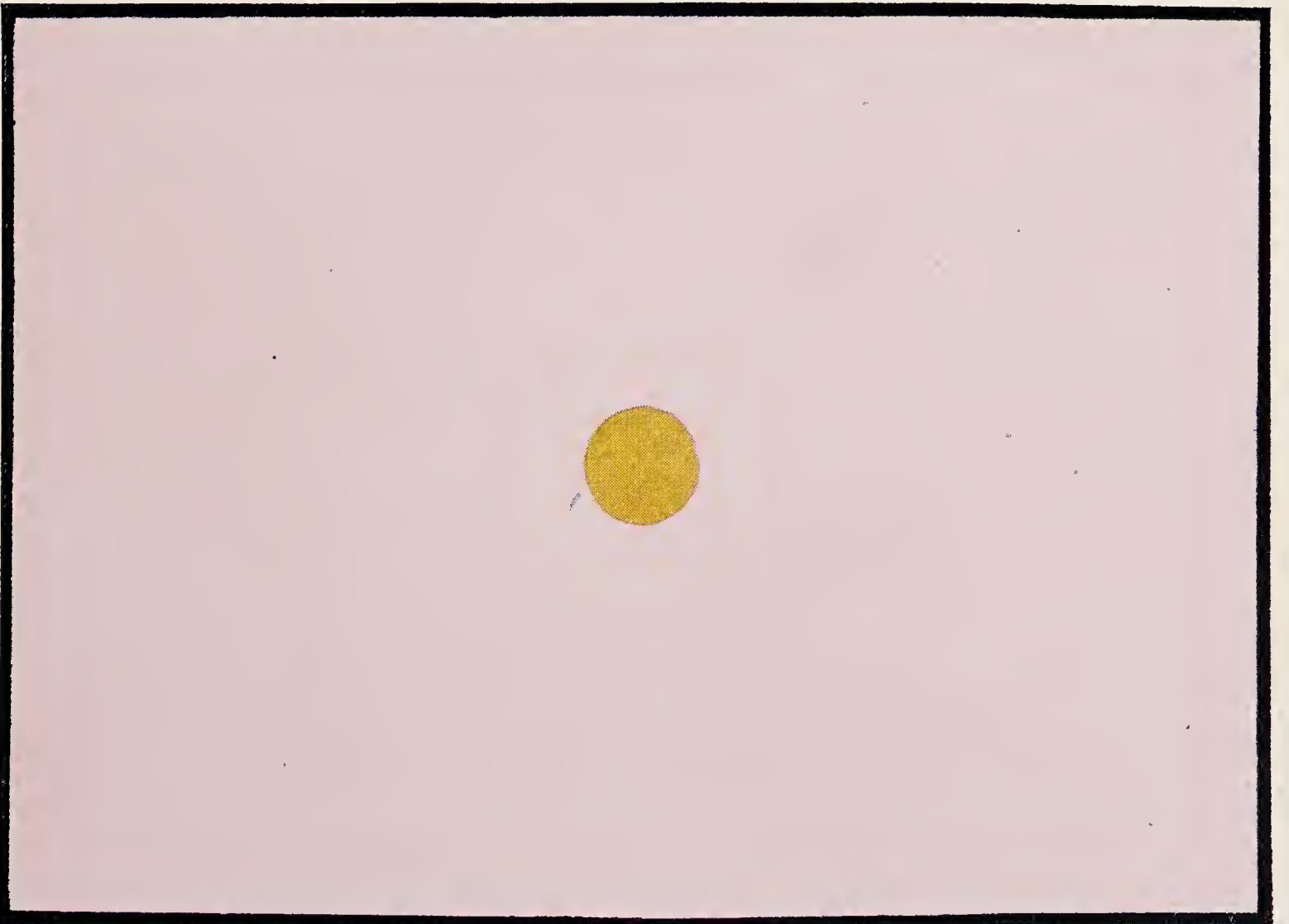


Figure 10. Picture of retina seen by light green filter.

or greenish-blue by transmitted light usually exhibit a cut-off at both ends of the visible spectrum. If the cut-off covers the yellow and orange regions of the spectrum, the retinal picture shows the fovea very clearly as an yellow ring with a bright yellow spot at the foveola (figures 4, 8 and 10). With the more deeply coloured filters, the foveal region appears also encircled by a halo or haloes (figure 6).

A variety of blue filters may be prepared by dyeing gelatine films on glass. All such filters cut off the yellow and orange regions of the spectrum, and hence when they are used, the fovea is invariably seen in the picture, the colour which it exhibits and the colour of the surrounding field varying with the nature of the spectral cut off by the filters. Very similar effects may also be observed using commercially available blue glasses. If such a filter cuts out the green, yellow and red sectors completely, its transmission is a clear deep blue of low intensity. When a filter of this kind is held against the eye against a bright background and then suddenly removed, a multi-coloured picture flashes into view in which the fovea with the foveola at its centre appears as a bright disc surrounded by a less luminous field and further encircled by a halo. This picture slowly fades away.

4. Observations with polarised light

The use of a polaroid in combination with a colour filter in observations of the kind described above reveals some highly significant facts. It may be stated at once that the special effects observed with polarised light are restricted to the foveal area on the retina. They are seen with filters transmitting the violet and blue sectors of the spectrum and are unobservable with filters which do not transmit those parts of the spectrum. The use of filters which transmit other parts of the spectrum besides the blue and the violet serves only to dilute the observed effects and make them less readily observable.

We shall now proceed to state what is actually observed. Placing a blue filter in front of the eye, a bright field of illumination is viewed; after a few minutes, a polaroid is placed in front of the filter. A dark brush shaped like a dumbbell crossed by a bright brush of similar shape then springs into view in the foveal area of vision. This picture slowly fades away. The polaroid is then suddenly removed, the blue filter remaining in place. *The brushes then reappear, but turned through a right angle, in other words, the bright brush takes the place of the dark brush and vice-versa.* This again duly fades away. The observations may be repeated as often as desired.

Observations of the same nature may also be made with the polaroid alone but without any colour-filter. Putting the polaroid in front of the eye, we observe the well-known phenomenon of Haidinger's brushes, a feeble yellow brush crossed by a blue brush appearing in the foveal area of vision. When this has faded away, the polaroid is suddenly removed. The brushes then reappear but with the yellow brush and the blue brush interchanged in their positions.

Another significant result emerges when the brightness of the field against which these brushes are viewed is varied. The polaroid and the blue filter should be used together so that the brushes are seen with the maximum clarity. Their fading-away is obviated by the simple device of oscillating the polaroid in its own plane through a right angle, so that the brushes remain continually visible, though constantly shifting their position. When the brightness of the field viewed by the observer through the polaroid-filter combination is progressively diminished. It is found that the visibility of the brushes vanishes when the level of illumination is reduced to the point at which the blue colour of the light becomes inconspicuous. In other words, the phenomena exhibited in polarised light are confined to the photopic levels of illumination and disappear when we pass into the scotopic range.

5. The visual pigments: Xanthophyll

We shall now proceed to make use of the facts and results set forth in the preceding pages to establish the chemical identity of the colouring matters present in the retina which enable it to function as a receptor of vision in the photopic range of illumination. The functioning of the retina in the lowest or scotopic levels of illumination will not be dealt with here.

Xanthophyll is a plant pigment of very wide occurrence. Its chemical name is dihydroxy- α -carotene and its chemical formula is $C_{40}H_{58}O_2$; it is dextro-rotatory and has no vitamin-A activity. The spectral properties of xanthophyll are similar to those of α -carotene. Xanthophyll is sensibly transparent for all wavelengths greater than $520\text{ m}\mu$; the absorption-strength becomes sensible at $500\text{ m}\mu$ and rises very steeply beyond $490\text{ m}\mu$; it reaches a pronounced maximum at $477\text{ m}\mu$ and this is followed by a second and even more pronounced maximum at $448\text{ m}\mu$. It falls off at shorter wavelengths and after exhibiting a third and minor maximum at $420\text{ m}\mu$ goes down steeply to small values beyond $400\text{ m}\mu$.

Like all the carotenoid pigments, xanthophyll exhibits in its structure a long chain of conjugated carbon-carbon double bonds, to which it owes its power to absorb light in the visible region of the spectrum. It may be remarked that this absorption appears only in the violet and blue sectors of the spectrum. The presence of xanthophyll in the retina is unquestionable. Indeed, the yellow colour of the *macula lutea* has long been known and that it is due to xanthophyll was established by extraction and the study of its absorption spectrum, notably by Wald. What we are now concerned with is to demonstrate that xanthophyll is the visual pigment which enables the eye to perceive light and colour in the violet and blue sectors of the spectrum. Several items of proof are forthcoming which will be set out in proper order.

The absorptive properties of xanthophyll account satisfactorily for the observed features of colour and luminosity in the spectrum. The region between 490 and $440\text{ m}\mu$ usually marked out as the blue sector in the spectrum is also the

region where the absorption of xanthophyll rises steeply from very small values to maximum strength. The region beyond $440\text{ m}\mu$ designated as the violet sector of the spectrum is also the region where the absorption of xanthophyll having passed its zenith drops down to small values.

The wavelengths at which the absorption-curve of xanthophyll exhibits its steepest gradients are also the wavelengths at which the hue-discrimination curve in the spectrum exhibits the most pronounced dips, in other words, the wavelengths at which the spectral shifts necessary to produce an observable change of colour reach their minimum values. The very steep rise in absorption at $490\text{ m}\mu$ corresponds exactly with the conspicuous dip of the hue-discrimination curve at $490\text{ m}\mu$. The second and much less conspicuous dip of the hue-discrimination curve at $440\text{ m}\mu$ also coincides in its position with the steep fall of the absorption of xanthophyll after it has reached its maximum value.

The effects observed with polarised light and described in the preceding section are a conclusive demonstration that xanthophyll is the visual pigment for the blue and violet sectors of the spectrum. They are explained as follows: Xanthophyll has long-chain molecules containing an alternation of single and double bonds; they can absorb light and function as a visual pigment only if the light is polarised with the electric vibrations parallel to the chain-structure of the molecules. On the slopes of the foveal area, the nerve fibres have a radial setting. In that region, therefore, the xanthophyll molecules lie parallel to the nerve fibres and also have a radial setting. Hence, in the foveal area, a bright brush is seen in the same plane as the electric vector of the incident light and a dark brush in the transverse direction. That the brushes are visible only in the blue and violet sectors of the spectrum and not elsewhere is readily intelligible. For, the absorption of light by xanthophyll appears only in the former regions and not elsewhere.

That the brushes reappear turned through a right angle following the removal of the polaroid has already been mentioned. This is a further proof that we are here concerned with a physiological phenomenon and not with an effect of physical origin. When the polaroid is kept before the eye long enough, the sensitivity of the foveal region to light is enhanced in the region of the dark brush and diminished in the region of the bright brush. Hence, when the polaroid is taken out, the brushes are seen again but with the dark and bright brushes exchanged in their positions.

Xanthophyll functions as a visual pigment only under photopic conditions. It is therefore to be expected that the brushes observed in polarised light over the area of foveal vision disappear when the illumination is reduced from the photopic to the scotopic level.

6. The visual pigments: Heme-proteins

The observations with colour filters described earlier make it evident that the pigments which enable the retina to function in the red and green sectors of the

spectrum are different. However, it is also clear from those observations that there is an overlap of the regions of the spectrum in which the two pigments function and that they co-operate in the perception of light and colour in the regions of such overlap. It is in these regions that the spectral colours of yellow and orange are perceived.

That the pigments which enable us to perceive the green and the red of the spectrum are heme-proteins of the ferrous and ferric types respectively is indicated by various considerations. In the first place, the absorption of light by these pigments appears in just those regions of the spectrum where they are needed to account for the observed facts of vision. Ferroheme exhibits a pronounced maximum of absorption around $550\text{ m}\mu$. Likewise, the luminous efficiency in the spectrum exhibits a highly pronounced maximum around $550\text{ m}\mu$. Accordingly, we are justified in recognising ferroheme as the visual pigment which functions in the green sector of the spectrum. Ferriheme behaves differently. Its absorptive power is much weaker than that of ferroheme in the green but is much stronger in the red. Hence, we are led to assign to ferriheme the role of the visual pigment which functions at the red end of the spectrum.

As is well-known, defects and anomalies in the perception of red and green in the spectrum are fairly common. It is very significant that these defects and anomalies are congenital and that they are transmitted from generation to generation according to the laws of heredity. Further, whereas the condition of night-blindness arising from dietary deficiency can be rapidly cured by an adequate addition of vitamin A to the food consumed, the defects of photopic colour-vision cannot thus be dealt with. These facts very clearly indicate that the visual pigments which enable us to perceive the green and the red of the spectrum are products of biological activity in the human body itself and that they are not plant products which have entered the retina by way of the articles of food consumed.

Having thus set aside the possibility of the carotenoids being the visual pigments for the green and the red, we naturally turn to the other great class of pigments of biological origin, viz., those in which the chromophore is a tetrapyrrolic group with a metallic atom located at its centre. Thus, by a simple process of exclusion, we are led to the identification of our visual pigments as heme-proteins, as already indicated. Heme is ubiquitous and we need therefore have no hesitation in assuming its presence in the retinal structures. The analogy with the activity of chlorophyll in the green leaves of plants indicates that heme which is a powerful absorber of light is also capable of transferring the energy absorbed to the retinal structures and thus enabling it to be perceived. Heme is also fairly stable chemically. Though a substantial fraction of the incident photons may be used up in effecting photochemical changes, enough would be left over to make vision in daylight both possible and efficient.

7. Defects and anomalies of colour vision

The characteristics of the rare condition known as tritanopia may be explained as arising from the absence of the pigment xanthophyll from the retina. The defects and anomalies of colour vision more commonly met with appear in the part of the spectrum between the termination of the blue and the extreme red end. The recognition that the heme pigments in the ferrous and ferric states are the mediators of vision in these regions makes these defects and anomalies explicable. Indeed, it is also possible to elucidate in detail the results of quantitative studies of those defects and anomalies. The subject has been fully discussed in an earlier memoir by the author¹. It will therefore suffice here to indicate broadly the approach developed in that publication.

As has already been explained, ferroheme is the visual pigment functioning in the green and ferriheme in the red; in the region of overlap of the absorption spectra of the two pigments, homogeneous light exhibits the various intermediate colours. The precise sequence of the luminosity and colour observed would evidently depend on the proportions of ferroheme and ferriheme functioning in the retina. The proportion in which iron is present in the ferrous and ferric states would presumably be determined by some regulating biochemical mechanism. Any malfunctioning of that mechanism would result in an alteration of the proportion in one direction or the other. This is the clue to the explanation of the observed deviations from the normal in the perception of light and colour.

If ferriheme be totally absent in the retinal pigment, the observer would fail to perceive the red end of the spectrum and the latter would therefore appear distinctly shortened. This is the state referred to as protanopic vision in the literature of the subject. If, on the other hand, the ferriheme is present in excess of the normal proportion, the region in which the two pigments function jointly would extend further towards the green. In consequence, the regular sequence of colour normally seen between the green and the red would tend to disappear. Ultimately, green and red would merge and be indistinguishable. This is the condition known as deuteranopia. Both in protanopia and in deuteranopia, the rapid change of hue appearing at $490\text{ m}\mu$ would be observable. In both cases also, the colour progression from the green to the red would be unobservable, but for wholly different reasons.

Protoanomalous and deuteranomalous vision may be considered as intermediate states between the normal condition and the conditions of protanopia and deuteranopia respectively. The luminosity and hue discrimination curves determined by observation for these anomalous types of vision are in satisfactory accord with the results to be expected on that basis.

¹ "The Perception of Light and Colour and the Physiology of Vision," Memoir No. 125 of the Raman Research Institute, *Proc. Indian Acad. Sci.*, A52, 255, 1960.

Light, colour and vision*

SIR C V RAMAN

I must thank the organisers for the honour of the invitation to address this Congress. I shall use the time at my disposal to dwell on the fundamental aspects of ophthalmology. We seek answers to the following questions. Firstly, what is the process by which our eyes are enabled to perceive light and colour? Secondly, what are the respective roles played by the retina and by the visual cortex in that process? It is obvious that the right answers to these questions can only be given if we understand correctly the physical nature of light and the manner in which it interacts with material bodies.

The nineteenth century physicists, notably Thomas Young, Hermann Von Helmholtz and Clerk-Maxwell who were interested in the problems of physiological optics were also the leading exponents of the wave-theory of light. That theory had many notable successes to its credit. Quite naturally, therefore, it was thought it could also form the basis for an understanding of the phenomena of vision. But this is not actually the case, for the concepts of the wave-theory of light are altogether irrelevant in relation to the interaction of light with material bodies. These interactions can be successfully described and understood only if it is recognised at the very outset that light consists of discrete units or quanta of energy. The interplay of light and matter is a process in which the quanta or energy-units in the radiation are transferred from the field to the material body or *vice-versa*. Unquestionably, therefore, the quantum theory is the proper basis for interpretation of the facts of visual experience.

The faculty that our eyes possess of perceiving colour brings the phenomena of vision into the closest relationship with the basic notions of the quantum theory. Light which appears as a sharply-defined line in the spectrum is composed of energy-quanta which are all equal. The quantum of energy varies with the position of the spectral line, being the lowest when it is at the red end and largest when it is at the violet end of the spectrum. Thus, the magnitude of the energy quantum varies *pari passu* with the colour of the perceived light. Every one of the many different colours we can perceive in the spectrum has, therefore, an equal claim with all the others to be regarded as a primary colour and as a fundamental visual sensation. This was indeed the original view expressed quite clearly by

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Isaac Newton in his celebrated treatise on optics. The widely prevalent belief that there are only three fundamental colours or only three fundamental visual sensations has no rational basis.

The ability to recognise closely adjacent regions of the spectrum as being different in colour is a faculty that our eyes possess. The perceivable differences in colour correspond over extensive regions in the spectrum to very small differences in the energy of the associated light-quanta. This leads us to adopt a very simple view of the functioning of the retina, namely that it absorbs the incident light-quantum and retransfers the energy absorbed through the nervous pathways to the optical cortex. The question then arises, what are the light-absorbing pigments present in the retina which enable it to perform this function? What are the spectral regions in which these pigments respectively operate and how are they distributed over its area?

A technique for the investigation of the retinal processes has been devised by me which is of extreme simplicity but nevertheless yields highly interesting and significant results. The observer holds a suitably chosen colour filter in front of his eye and views an extended and brightly illuminated screen through the filter. After a brief interval of time, the filter is suddenly removed. What is then observed depends very much on the colour filter employed and especially on the part of the spectrum which the filter absorbs and the part which it transmits freely.

By way of illustration, it will suffice here to mention two strikingly contrasted cases. When a filter dyed with methyl violet which cuts out the yellow part of the spectrum around 5800 \AA is held before the eye and then suddenly removed, the observer sees projected on the viewing screen a highly magnified picture in colours of his own retina in which the fovea and its central depression stand out conspicuously by reason of their differences in colour and brightness from the surrounding areas. On the other hand, when a filter dyed with eosine which shows an absorption band in the green around 5300 \AA is put in and then removed, the screen presents the same appearance before the filter is put in and after it has been removed.

Using various colour filters, we can explore the entire spectrum from end to end by this technique. The result emerges that the visible spectrum can be demarcated into four sectors. The first sector is the part between the violet end and the wavelength at which the colour changes rapidly from blue to green. In the second sector, the visual luminosity of the spectrum increases progressively and reaches a maximum. In the third sector, the observed colour progressively changes from green to red. The fourth sector is the red end of the spectrum.

We now proceed to the identification of the materials present in the retina which function respectively in these four sectors. We shall take them in order.

Xanthophyll is the visual pigment which functions in the first sector and enables us to perceive the colours ranging from violet to blue. It is a yellow carotenoid pigment of vegetable origin which is present in all green plants and enters the human body through the medium of the food products consumed. It is

present in the retina as the well-known yellow macular pigmentation. That it is indeed a visual pigment is indicated by the fact that the range of wavelengths in which the perceived colour changes very rapidly from blue to green is precisely the same as that in which the absorptive power of xanthophyll drops suddenly from a large value to zero. A further demonstration that xanthophyll functions as a visual pigment is furnished by the effects seen by an observer who views an extended source of light through a polaroid and a colour filter transmitting only the blue part of the spectrum. The observer sees an image of his own fovea projected against the source of light in which a bright brush and a dark brush appear crossing each other. This phenomenon is observed only when the illumination of the field is in the photopic levels and it disappears completely when the brightness is reduced to the scotopic level. The brushes appear as a consequence of the shape and optical properties of the xanthophyll molecules. These orientate themselves parallel to the nerve fibres and hence are arranged radially in the foveal area. They absorb light and function as a visual pigment only in respect of vibrations parallel to the chain of eleven double bonds contained in the molecule.

Various considerations which cannot here be set out in detail serve to exclude the possibility of the visual pigments functioning in the three other sectors of the spectrum being carotenoids. The pigment which actually functions in the second or green sector of the spectrum is heme in which the iron atom located at the centre of the tetrapyrrolic group is in the ferrous state. Heme in the ferrous state exhibits a powerful absorption of light between 5000 and 6000 Å, the maximum of absorption being located at 5600 Å. The wavelength of maximum visual luminosity in the spectrum is also 5600 Å. Thus, by reason of its structure and spectroscopic behaviour, heme in the ferrous state fits perfectly into the role of the principal visual pigment. One more function is thus added to the many important roles which heme plays in the field of biology.

When the iron atom at the centre of the tetrapyrrolic group in the molecules of heme is in the ferric state, the absorption spectrum undergoes a radical change, the principal feature being an extension towards greater wavelengths and a greatly increased strength of absorption in the region between 6000 and 7000 Å. Thus, heme in the ferric state fits into the role of the visual pigment which functions in the fourth or red sector of the spectrum. The third sector in which the transitional colours of yellow and orange appear is clearly the part of the spectrum in which the ferrous and ferric states of heme function in co-operation with each other.

The time at my disposal does not permit of my dealing in detail with the problems of anomalous colour-vision. It will suffice here to state that the existence of such anomalies and their observed characteristics find a natural explanation on the basis of the present approach to the theory of vision. These and various other matters will be found discussed in detail in a memoir published by me two years ago.

Floral colours and their spectral composition

SIR C V RAMAN

1. Introduction

The leaves and flowers of plants are the most familiar objects manifesting colour met with in the organic world. It follows that the nature and origin of these colours is well worth of detailed study. The chemical constitution of the pigments present in plant products and capable of extraction therefrom by suitable solvents has been the subject of numerous investigations in the past. But there is another point of view from which the subject can be regarded. The colours exhibited by the leaves and flowers of plants are determined by the spectroscopic behaviour of the material *in vivo*, and this can be studied by quite simple methods. We have only to observe the changes in the spectral character of the light produced by its entry into the material and subsequent emergence from it, as a result of absorption and diffusion within the substance. The observation of these changes may be expected to throw some light on the nature of the material. Further, it should be remarked that the relationship between the spectral character of the emerging light and the observed colour of the leaves or flowers is of great interest from the standpoint of physiological optics.

The present communication is in the nature of a preliminary survey of the subject. It will be seen, however, that some highly significant results have emerged from it.

2. Origin of the green colour of leaves

The most familiar of all plant colours is the characteristic green hue exhibited by the foliage of the great majority of trees, shrubs and other forms of vegetation. We shall therefore begin by considering the question how this colour originates. A very simple technique suffices to furnish the necessary information. We hold the leaf in a beam of sunlight and examine the light which emerges from it through a pocket-spectroscope of the direct-vision type. The instrument should be provided with a wavelength scale capable of being focused independently and also capable of being adjusted so that the wavelength readings check with those of the lines in the solar spectrum.

It is well-known that the foliage of different species of plants is often noticeably

different in colour. Further, fresh leaves which have just emerged and have not yet attained maturity often exhibit tints different from those of fully developed leaves of the same species. We are, however, here concerned with the features exhibited by green leaves in general. Hence, it is convenient to make observations with plants in which the colour of the leaves is a clear green at all stages of development and exhibits only the changes accompanying the increased thickness due to growth.

The spectrum of the light which emerges from the rear of a green leaf on the front face of which sunlight is incident may be divided into three parts: (a) the first between 400 and 520 $m\mu$, (b) the second from 520 to 640 $m\mu$ and (c) the third from 640 to 700 $m\mu$. The transmission in the violet and blue regions of the spectrum becomes very weak with increasing thickness of the leaf, and the wavelengths less than 520 $m\mu$ are then effectively cut off. On the other hand, the region between 640 $m\mu$ and the extreme red end of the spectrum is itself intrinsically very weak to our perceptions. However, when the leaf is not very thick and it is held up in sunlight, this part of the spectrum can be seen coming through weakly, and the absorption bands due to chlorophyll in the (a) and (b) forms can be recognised in it. It is evident, however, that these bands appearing in a region of very low luminosity cannot influence the observed colour of the emerging light to any appreciable extent. We have, in fact, to consider only the spectral region between 520 and 640 $m\mu$ covering the green, yellow and orange sectors and the brightest part of the red in the determination of the resultant effect.

A comparison of the light emerging through a green leaf and that which has passed through the petals of a flower having a golden-yellow colour is very instructive. Flowers of the latter variety are very numerous, and it does not much matter which particular one is chosen for the comparison. The brightness of the light emerging from the petal may, if necessary, be reduced by holding two of them together, so that the intensities observable in the spectrum of the flower may be comparable with those in the light transmitted by the green leaf under study. It will be found that the extension of the spectrum observable in the two cases is not appreciably different, being between 520 and 640 $m\mu$ for the green leaf, and between 520 and 650 $m\mu$ for the golden-yellow flower petal. It is evident that the slightly greater extension towards the red end observed in the spectrum of the flower petals cannot account for the enormous difference in colour between a golden yellow and a bright green. Indeed, the similarity of the two spectra is a most surprising and unexpected feature. Careful examination, however, reveals that the spectrum of the green leaf shows a low intensity in the spectral region between 560 and 620 $m\mu$ as compared with the intensity in the same region of the yellow flower petals. It is clear from these observations that it is the absorption in the yellow and orange sectors of the spectrum and not the absorption in the red sector which is the operative factor resulting in the green colour of the leaves. The absorption by the two forms of chlorophyll in the wavelength range under reference, viz., between 560 and 620 $m\mu$ is weak compared with the principal

absorptions by them appearing in the red sector of the spectrum. But it is nevertheless the former and not the latter that results in our perceiving the characteristic green colour of the foliage of plants.

3. The spectrum of the "Morning Glory"

We shall next consider the remarkably interesting case of the flower known popularly as the "Morning Glory", the botanical name of the plant being "*Ipomea learii*". This plant is a creeper which when trained over a screen presents a magnificent sight in the early mornings with its green foliage studded over with large trumpet-shaped flowers of a deep blue colour. These show five divisions exhibiting the blue colour which are held together by narrow ribs of a purplish tint. The colour of the flowers is a highly saturated blue and may indeed be described as exhibiting spectral purity. It is distinctly more so when seen from the front by reflected light than as observed from the rear by transmitted light. That this difference is due to the extreme thinness of the petals is clear from the fact that when two of them are held together and the absorption path thereby doubled, the colour as seen by transmission is more highly saturated.

The spectrum of the "Morning Glory" may be observed either by the light reflected or by the light transmitted by the flower. In either case the entire spectrum extending from the extreme violet to the extreme red may be seen without any noticeable change in the relative intensities of its different parts as compared with the light reflected by a white sheet of paper, *except* in the wavelength range between 570 and 630 $m\mu$; this spectral region is much diminished in brightness and a practically complete cut-off appears between 600 and 630 $m\mu$. To exhibit this feature, the spectrum of the transmitted light was photographed with a Hilger constant-deviation spectrograph on an Agfa panchromatic film. A tungsten filament lamp was used as the source of light in conjunction with a filter of copper sulphate solution so as to reproduce daylight conditions as nearly as practicable. Spectrograms obtained with three different exposures are reproduced together in figure 1, the first and the last in the series of five spectrograms being the comparison spectra exhibiting the light of the source employed. A dark band is very clearly seen in the three spectrograms not far from the red end of the spectrum, but clearly separated from it.

The "Morning Glory" thus presents us with the surprising fact that the weakening or removal from the spectrum of white light of a narrow strip covering its yellow and orange sectors transforms the resulting visual sensation from a pure white to a highly saturated blue closely resembling a pure spectral colour. As observed visually and as also shown by the spectrograms reproduced, the light which produces this sensation has its red, green, blue and violet sectors present in full strength and yet it does not excite in any observable degree the achromatic sensation which should, accordingly to the generally accepted beliefs, result from

their superposition. These facts are highly significant in relation to our fundamental notions regarding physiological optics and the theory of colour perception.

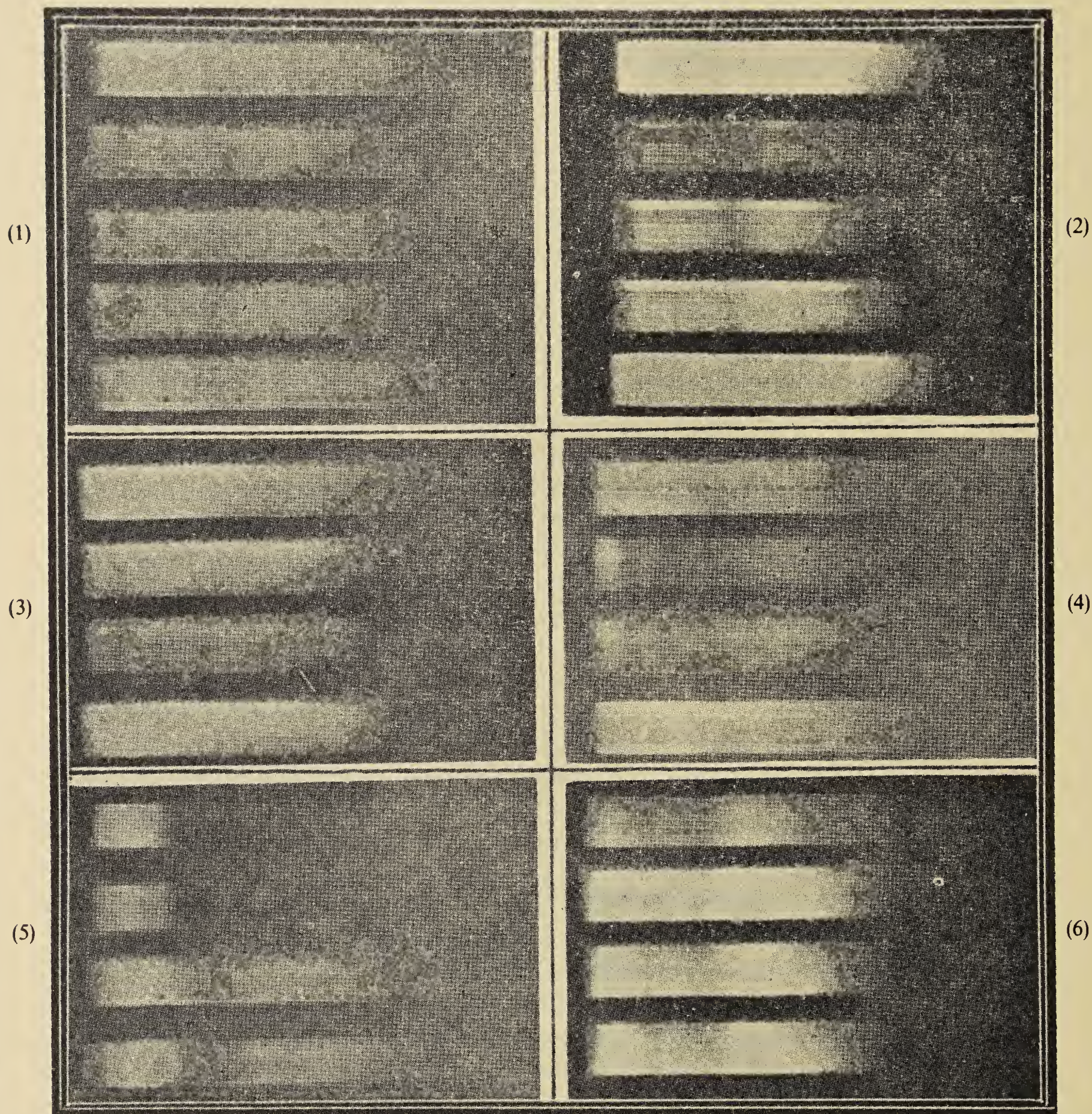
4. The spectrum of the blue lotus

The lotus is one of the most famous and best-loved flowers of India. In the sunken garden attached to the author's residence at Bangalore, the floating leaves and blue flowers of a lotus make a most colourful exhibit in a large cistern of water. The petals of the lotus exhibit a purplish-blue colour which, though not so saturated as the blue of the "Morning Glory", nevertheless is very impressive by reason of the large number and geometric arrangement of the petals. The spectrum of the colour is readily observed either by reflection or by transmission. As in the case of the "Morning Glory", the violet, blue-green and red regions of the spectrum appear without any noticeable alteration of their relative intensities; but the spectral region between 550 and 610 $m\mu$ appears much weakened in its intensity, and *two* dark bands clearly separated from each other are noticeable in it. One of the bands appears between 550 and 570 $m\mu$, and the other between 590 and 610 $m\mu$, the latter being the stronger and better defined absorption of the two. The differences in colour and the degree of its saturation in the case of the two flowers thus correspond to the differences in the spectral composition of the light in the two cases.

5. The blue of the Jacaranda

Many flowering trees are known in India which in the appropriate seasons of the year array themselves in flower-mantles of spectacular beauty. The Jacaranda of which the full botanical name is *Jacaranda mimosifolia* is singled out here by reason of the unique character of its floral display. In the month of March each year, it bursts into flower and is then one of the most striking exhibitions of colour which could be imagined. The number of individual flowers on each tree is so enormous and they are so densely aggregated that each tree appears to carry a "blue mist" on its head. A whole avenue of such trees is an unforgettable sight.

The colour of the Jacaranda flowers is more nearly violet than blue. When freshly removed from the tree, they exhibit a vivid but not a saturated hue. But the colour becomes more vivid as the flower dries up. Its spectrum may be examined either by transmitted or by reflected light. Two absorption bands are noticeable, one between 580 and 600 $m\mu$ covering the yellow region of the spectrum and another in the red beyond 630 $m\mu$. The orange sector of the spectrum between 600 and 630 $m\mu$ stands out as a bright strip between these two absorption bands. The third of the five spectrograms, reproduced in figure 2, shows this effect clearly, the



Figures 1–6. Spectra of flower petals by transmitted light. 1. “Morning Glory” with comparison spectra. 2. Jacaranda with comparison spectra. 3. “Heavenly Blue” (two petals) with comparison spectra. 4. Ground-Orchid with comparison spectra. 5. “Cloth of Gold” two petals and one petal. 6. After with purple petals.

first and the fifth in the group being the comparison spectra of the light source employed. Though the absorption in the yellow between 580 and 600 $m\mu$ is not very conspicuous, it nevertheless plays the major role in determining the colourful appearance of the Jacaranda flowers, since the red end of the spectrum where the second absorption appears is intrinsically of low luminosity to our perceptions.

We may also refer here to two other plants which are well known and the spectral behaviour of whose flowers somewhat resemble those of the Jacaranda. One of them is the creeper known botanically as *Thunbergia grandiflora* which bears large five-lobed flowers popularly known as the "Heavenly Blue". The other is *Plumbago capensis* which is commonly planted out as hedges by reason of its bearing numerous clusters of small pale-blue flowers which make a fine show against the green foliage of the plant. Holding two of the lobes of the "Heavenly Blue" flower one behind the other, the transmitted light appears of a deeper blue than with one flower alone, and the absorption band in the yellow between 580 and 600 $m\mu$ is then more conspicuous. A succession of fainter bands can also be seen in the region of smaller wavelengths. This effect is reproduced in figure 3. Very similar effects may also be observed with the *Plumbago capensis* flowers if they are bunched together, thereby increasing the absorption paths in the material.

6. Flowers exhibiting band spectra

Of particular interest to the spectroscopist are those flowers which exhibit regularly-spaced band spectra in the light reflected by or transmitted through their petals. One such plant is a ground-orchid in the author's garden which bears elongated leaves like those of a palm and also carries long green stalks on which the flowers come out in succession, making a colourful show. The flowers have five petals of a reddish purple hue, and when viewed through a pocket spectroscope they exhibit a succession of bright and dark bands, as shown in the two spectrograms reproduced in figure 4 between the two comparison spectra of the light-source. The first dark band is very dark and sharp and appears at 590 $m\mu$. The second dark band is somewhat broader but nearly as dark and appears at 545 $m\mu$. The third dark band is rather diffuse and appears at about 505 $m\mu$. The elimination of the yellow sector of the spectrum and the weakening of the green sector by the dark bands appearing in it are evidently responsible for the colour exhibited by the flower.

The flowers of the well-known garden shrub known as the *Cineraria* are also found to exhibit the band spectra in a conspicuous manner. Particularly striking in this respect are those varieties in which the petals exhibit a purplish-red hue. The band system in these cases resemble that observed with the ground-orchid described above and illustrated in figure 4. On the other hand, the varieties in

which the petals are of a bluish-purple hue give a different type of spectra. The first bright band in the orange-red sector appears split into two, and the other bands also exhibit indications of such splitting. The blue flowers of the larkspur are also found to exhibit a set of rather closely-spaced bands in the red, orange and yellow sectors of the spectrum.

The question naturally arises why the absorption spectra exhibit a succession of dark and bright bands in the cases described. The suggestion may be ventured that we are perhaps concerned with a superposition of the vibrational and of the electronic absorption spectra of the molecules of the pigments present in the flowers.

7. The spectrum of the "Cloth-of-gold"

As has been remarked earlier, a great many flowers are known which exhibit a golden-yellow colour, and their spectra are usually very similar to each other. The faintest yellow indicates the presence of a sensible absorption in the region of shorter wavelengths in the spectrum. The deeper the colour, the further has the absorption advanced from the violet into the blue and then towards the green. A change from yellow to orange indicates that the absorption has entered well into the green sector of the spectrum. The further the absorption advances into the green, the deeper becomes the orange hue. It then passes over into orange-red and finally into a scarlet colour.

The absorption by yellow flowers in the violet and blue sectors of the spectrum is usually so strong as to result in a complete cut-off of those regions. When the petals are very thin, however, it is possible with longer exposures photographically to record a feeble transmission in the blue and the violet sectors. It is interesting to remark that the transmission then appears as a succession of bands clearly resolved from each other.

The four spectrograms reproduced as figure 5 were recorded with the petals of a flower which is grown extensively in South India and finds a large market. It is known as "Kanakambaram" which may be translated into English as the "Cloth-of-Gold". The flower is of a beautiful orange-yellow tint. The individual petals are so thin that there is a sensible transmission over the entire spectrum which however exhibits a succession of bands, as can be seen in the third and fourth of the spectrograms reproduced as figure 5. When two petals are held together, however, the shorter wavelengths are cut off and only three bands are recorded, as can be seen in the first two spectrograms in figure 5. It would be interesting to ascertain the chemical constitution of the colouring matter which gives these remarkable effects.

The trichromatic hypothesis

SIR C V RAMAN

“My design in this book is not to explain the properties of light by hypotheses, but to propose and prove them by reason and experiments.” So reads the opening sentence of Newton’s classical work on optics in the first book of which the foundations of the theory of colour were firmly laid and a bridge thus built between the physics and the physiology of vision. Precisely what Newton had in mind when he made the reference to hypotheses contained in this sentence may be inferred from the following passage which appears towards the end of his book. “As in mathematics so in natural philosophy, the investigation of difficult things by the method of analysis ought ever to precede the method of composition. This analysis consists in making experiments and observations, and in drawing general conclusions from them by induction and admitting of no objection against the conclusions but such as are taken from experiments, or other certain truths. For hypotheses are not to be regarded in experimental philosophy.” From these remarks it is clear that the hypotheses which Newton had in mind are assumptions of an arbitrary character not based on well established facts of observation.

Newton’s aversion to hypotheses was not unjustified. For, there is a danger in adopting hypotheses when no real knowledge is available of the facts of the subject. A species of self-deception then becomes possible leading one to beliefs which are either wholly unjustified or else are only half-truths. Further, they are liable to make one blind to facts which come to light later and which are themselves a patent contradiction of the hypothetical assumptions. These remarks are made here with special reference to the hypothesis originally put forward by Thomas Young and now known and referred to generally as the trichromatic theory of vision. That the theory is based on *ad hoc* assumptions and not on any well-established facts will be made clear later on. It will suffice here to mention that Young himself thought that the three primary sensations were those of red, yellow and blue, and later changed over to red, green and violet as a better choice. But before commenting any further on Young’s hypothesis and its subsequent history, it appears desirable in the first instance to state the actual facts of the subject.

We may usefully begin by quoting in Newton’s own words the conclusions which he arrived at as the result of his studies on colour. In characteristic fashion, he summed them up in two “definitions” which are reproduced below verbatim:

Definition VII: *The Light whose Rays are all alike Refrangible, I call Simple, Homogeneous and Similar; and that whose Rays are some more Refrangible than others. I call Compound, Heterogeneous and Dissimilar.* The former Light I call Homogeneous, not because I would affirm it so in all respects, but because the Rays which agree in Refrangibility, agree at least in all those their other Properties which I consider in the following Discourse.

Definition VIII: *The Colours of Homogeneous Lights, I call Primary, Homogeneous and Simple; and those of Heterogeneous Lights, Heterogeneous and Compound.* For these are always compounded of the colours of Homogeneous Lights; as will appear in the following Discourse.

Newton's ideas are very clearly expressed in the foregoing extracts. In the first place, he recognised that the physically simplest forms of light—which we would describe today as radiations manifesting themselves as single sharp lines in the spectrum—are also the exciters of the primary or simple physiological sensations which are the pure colours of the spectrum. Newton also recognised that the sensations excited by polychromatic light are compounded of these primary sensations and are, therefore, necessarily of a more complex character.

That the sensations excited by monochromatic light are the primary physiological sensations and that these are quite as numerous as the colours which can be perceived as distinct from each other in a pure spectrum is established by various facts of observation. On no other basis can a reasonable explanation be offered for the fact that our visual faculties enable us to distinguish between the colour of closely adjacent regions in the spectrum. Indeed, in some parts of the spectrum, a difference of as little as 10 \AA in the wavelength of the light suffices to produce an observable difference in colour. Then again, if monochromatic light be admixed with white light, we can still perceive and recognise the colour in such admixture and what is perhaps even more significant is that our ability to discriminate between the colours of closely adjacent regions of the spectrum is not altered appreciably even when they are both admixed with substantial proportions of white light.

Light, according to Newton's ideas expounded in the third book of his treatise, is of a corpuscular nature. In other words, it consists of small bodies emitted by the source of light, their sizes being different for the differently coloured rays of the spectrum and altering continuously as we pass from one end of the visible spectrum to the other. On this basis, the existence of a definite relationship between the refrangibility of light and its observed colour is only to be expected. To quote Newton's own words, "nothing more is requisite for producing all the variety of colours, and degrees of refrangibility, than that the Rays of Light be Bodies of different Sizes". It was inevitable, therefore, that Newton should recognize the colours of the spectrum as the primary, homogeneous, and simple colours and the colours of lights of different sorts mixed with each other as heterogeneous and compound.

The corpuscular view of the nature of light favoured by Newton fell into disrepute during the nineteenth century. It was no accident that the physicists who were associated with the development of the wave-theory of light thought fit to reject Newton's conclusions regarding colour and its perception and attempted to replace them by other assumptions of a hypothetical nature. They could not have foreseen that all such attempts were foredoomed to failure and that the corpuscular concept of light would emerge once again, triumphantly vindicated. The different sizes of the particles of light contemplated by Newton are replaced by the different magnitudes of the energy-quanta which they represent.

It is a fact of observation that the eye can discern some 150 or more different hues in the spectrum. Rejecting this as an inexplicable achievement of our faculty of vision, Young postulated that there are only three different "principal" colours and that the rest are only derivatives. The question then arose, which three colours should be chosen as the "principals". Young's first choice was that of the colours red, yellow and blue. Later, he discarded these and adopted red, green and violet as his favourites. He then drew an equilateral triangle having these three colours at the vertices, white at the centre and the other spectral colours as points lying on its two sides.

Young's triangle of colours was just pure phantasy. For, later studies have shown in the most conclusive manner that the pure colours of the spectrum stand in a category by themselves and that they cannot be equated to the result of any superposition of other colours. This fact alone is sufficient to prove the correctness of Newton's analysis of the subject of colour and is a shattering blow to the ideas underlying the trichromatic hypothesis. But, as has been remarked earlier, believers in *ad hoc* hypotheses do not readily admit defeat when confronted by the discovery of new facts. They assiduously seek to find ways of escape from the consequences of such discoveries.

One of the several ways in which it has been sought to bolster up a belief in the validity of the trichromatic theory, instead of allowing it to join the limbo of discarded hypotheses, has been to suggest that all observable colours could be represented as equivalent to the result of superposing three suitably chosen colours in suitably chosen proportions. The equivalence is represented in the form of an algebraic equation, quantities being introduced therein known respectively as trichromatic coefficients and tristimulus values, suggestive of a mysterious power and significance for the number three in colour theory. Geometric representations have also been devised in which colours were represented as points in a system of trilinear co-ordinates. A critical examination of these representations of colour shows, however, that they are devoid of any real physical significance. This becomes evident when it is remarked that in the XYZ system which is generally adopted for the geometric representation of colour, the vertices X, Y, Z of the triangle do not represent any real physical colours, the entire triangle lying outside the area in which the points representing actual colours lie. Indeed, these representations mean little more than that any actually

observed colour resembles the result of superposing an achromatic sensation upon a recognisable colour with a saturated hue, a fact which was known to and stated quite clearly by Newton in his treatise.

The subject of the sensations excited on our visual organs by polychromatic radiations is one of considerable interest and importance. One has only to recall the vast number of possibilities included in the words "polychromatic radiation" to appreciate that only observational data obtained on the widest possible basis and by methods not influenced by bias of any sort could be expected to reveal the real facts of the subject. So far from the trichromatic theory of vision having been of any real assistance towards the understanding of this difficult and complex field, it has only served to introduce error and confusion and stood in the way of any real advances in knowledge.

Floral colours and the physiology of vision

SIR C V RAMAN

The world of flowers provides us with an illimitable variety of objects manifesting colour to our visual perceptions. How do these colours arise? The issues raised by this question would be regarded from entirely different points of view by men of science according to their professional interests. But the most fundamental issue of all is the relationship which exists between our visual perceptions and the spectral composition of the light which reaches our eyes from the material of the flower. This relationship can be studied by very simple methods which enable a great many cases to be rapidly surveyed and thereby permit of some conclusions of general validity to be reached. Such an investigation has occupied the author during these past few months and the results which it has yielded are of extraordinary interest and importance. Indeed, it appears that a radical reconstruction of our ideas regarding the physiology of vision and the perception of colour is called for in the light of the facts revealed by the investigation.

The colours of the spectrum, in other words, the sensations excited in our visual organs by the monochromatic radiations into which white light is split by a prism or a diffraction grating, form the natural and indeed the most appropriate standard of comparison with any observed colour and therefore also the basis of the language in which any observed colour should be described. But the distinguishable colours of the spectrum are very numerous, and a further difficulty is raised by the fact that many observable colours appear to our perceptions to differ fundamentally from any of the pure spectral colours. In these circumstances, the question of terminology complicates the task of describing the results of a study which seeks to specify the relationship between any perceived colour and the spectral composition of the light which gives rise to that sensation. Fortunately, however, it turns out that this difficulty is not insuperable and that the results of the study can be set out in readily intelligible terms.

The sensation known as purple is one that is readily recognised by all who are familiar with the subject of colour and we shall therefore begin by considering the origin of this sensation as revealed by the present investigation. It is appropriate that we consider first the case of a plant which is accessible to the widest possible circle of readers. Balsam is a well known garden plant which also goes by the name *Impatiens* by reason of the violent discharge of its seeds from the pod when ripe. The flowers appear along the entire stem of the plant. One of the known varieties of balsam advertised in the seedsmen's catalogues bears purple flowers.

Holding up the petals of this flower against the sky, a visual examination of the light emerging through it with a pocket spectroscope reveals that the petals exercise a powerful absorption in the spectral region between 560 and 590 $m\mu$, the strength of such absorption visibly increasing as we proceed towards greater wavelengths and being greatest at 590 $m\mu$. In other words, the petal absorbs the yellow region of the spectrum strongly, whereas the rest of the spectrum is let through the different regions therein exhibiting the same relative intensities as in the incident light. Another method of examination is to view the petal in sunlight by reflection instead of by transmission. The spectrum seen in this way represents the colour of the flower more nearly than the spectrum observed by transmission. Actually, however, in the particular case, there is no noticeable difference in the characters of the observed spectra.

As another noteworthy example of a purple flower may be mentioned here the blooms of the great forest tree known as *Lagerstroemia Flos-Regina*, the striking beauty of which in the flowering months has led to its being planted extensively as ornamental trees in gardens and in avenues. There are two varieties of this tree, one of which bears purple flowers and the other rose-coloured ones. We shall return to the second kind later on. The flowers of *Lagerstroemia* have very thin and delicate petals, but their colours are extremely striking. The spectral behaviour of the purple variety is the same as that of the balsam flowers described earlier. This is also true of numerous other flowers which exhibit a purple hue to our visual perceptions. The well-attested fact thus emerges that the weakening or removal of the yellow sector of the spectrum between 560 and 590 $m\mu$ from the light entering the material of the flower and re-emerging as scattered or diffused light results in the latter exhibiting to our visual perceptions the characteristic sensation of a purple colour.

In the foregoing paragraph, reference was made to the rose-coloured flowers borne by the second variety of *Lagerstroemia Flos-Regina*. Spectroscopic examination of these rose-coloured flowers reveals that their petals exercise an observable absorption in the spectral region between 510 and 570 $m\mu$, the maximum of absorption being at 550 $m\mu$. There is no sensible absorption at wavelengths less than 510 $m\mu$ or greater than 570 $m\mu$. In other words, the petals of the rose-coloured flowers present a sensible absorption in the green sector of the spectrum, but allow the violet and blue as well as the yellow, orange and red parts of the spectrum, to come through freely. The manifestation of a rose-red colour to our perceptions is thus associated with the spectral behaviour just mentioned.

A rose-red colour is exhibited by numerous other flowers. A highly significant fact which has emerged from the studies made by the author with such flowers is that the saturation of the observed hue increases *pari passu* with increasing strength of the absorption manifested in the green sector, the rest of the spectrum retaining its characteristic of free transmission. In other words, the more nearly complete the absorption of the green is, the more nearly does the observed hue approach a spectral red in its visual characters. This feature is noticeable with

many flowers, a particularly remarkable fact being that their perceived colour is red, despite the fact that the spectroscope shows the blue of the spectrum appearing with undiminished intensity relatively to the red, orange and yellow parts of the spectrum. In some cases, indeed, the perceived colour is indistinguishable from a pure spectral red, but the spectroscopic examination shows the blue coming through with no observable diminution in its intensity.

The facts set forth above are so remarkable in themselves and so different from what the current beliefs regarding the origins of colour would indicate that it appeared desirable to present to the reader some evidence of an objective nature supporting the statements made on the basis of subjective observations. In the course of the author's investigations, indeed, numerous spectrograms were recorded of the light transmitted through various flower petals. A complication that presented itself in this work was the non-uniform sensitivity of the panchromatic film employed to record the spectrograms. This shows up as a very pronounced minimum of recorded intensity in the green region. In consequence of this, the photographic record of the transmission spectra is not as satisfactory an indication of the real behaviour of the flower petal as could be desired. Nevertheless, the records are not altogether useless for the purpose in view.

Figure 1 in the accompanying reproduction exhibits three spectrograms recorded with three different exposures of the light of a tungsten filament lamp (filtered through CuSO_4 solution) and transmitted through the petal of a purple balsam flower. Above them appears a comparison spectrum of the light source. The red end of the spectra appears at the extreme left in each case, while the blue and violet regions stretch out to the right. The sharp cut-off seen visually at $590\text{ m}\mu$ and the rapid decrease in the absorption at smaller wavelengths are both clearly shown in the spectrograms.

Figure 2 reproduces the absorption spectra (recorded in a similar manner) of the petal of a polyantha rose. This was chosen for the reason that its red colour was of nearly saturated hue. On a comparison with figure 1, it will be seen that the absorption in figure 2 begins at a greater wavelength and extends over nearly the whole of the green sector. It is significant that the blue and violet regions of the spectrum appear in the transmitted light without any observable indications of absorption.

Numerous flowers the colour of which appears blue to our visual perceptions were also studied. It was a noteworthy fact that none of those so far examined exhibited any localised increase of intensity in the regions of shorter wavelengths in the spectrum. On the other hand, the spectroscope showed very clearly that the observed colour had its origin elsewhere in the spectrum. We may mention here three flowers exhibiting a blue colour which were studied in some detail, viz., the flowers of the avenue tree *Jacaranda mimosifolia*, the flowers of the climbing plant *Thunbergia grandiflora*, and the clusters of blue flowers of the well known shrub *Plumbago capensis*. In each of these cases, the most conspicuous feature of the spectrum was an absorption band from 560 to $590\text{ m}\mu$ covering the yellow region.

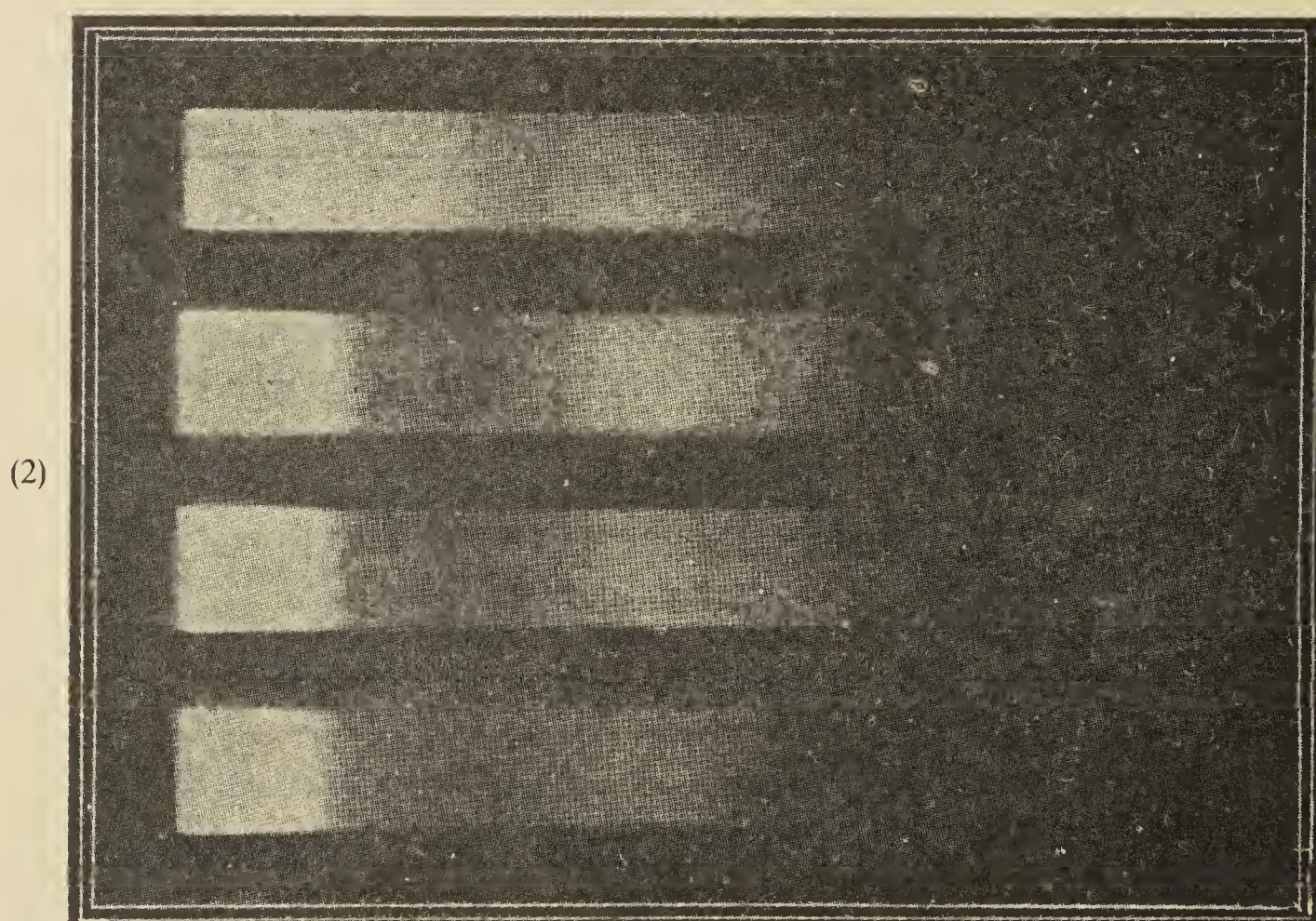
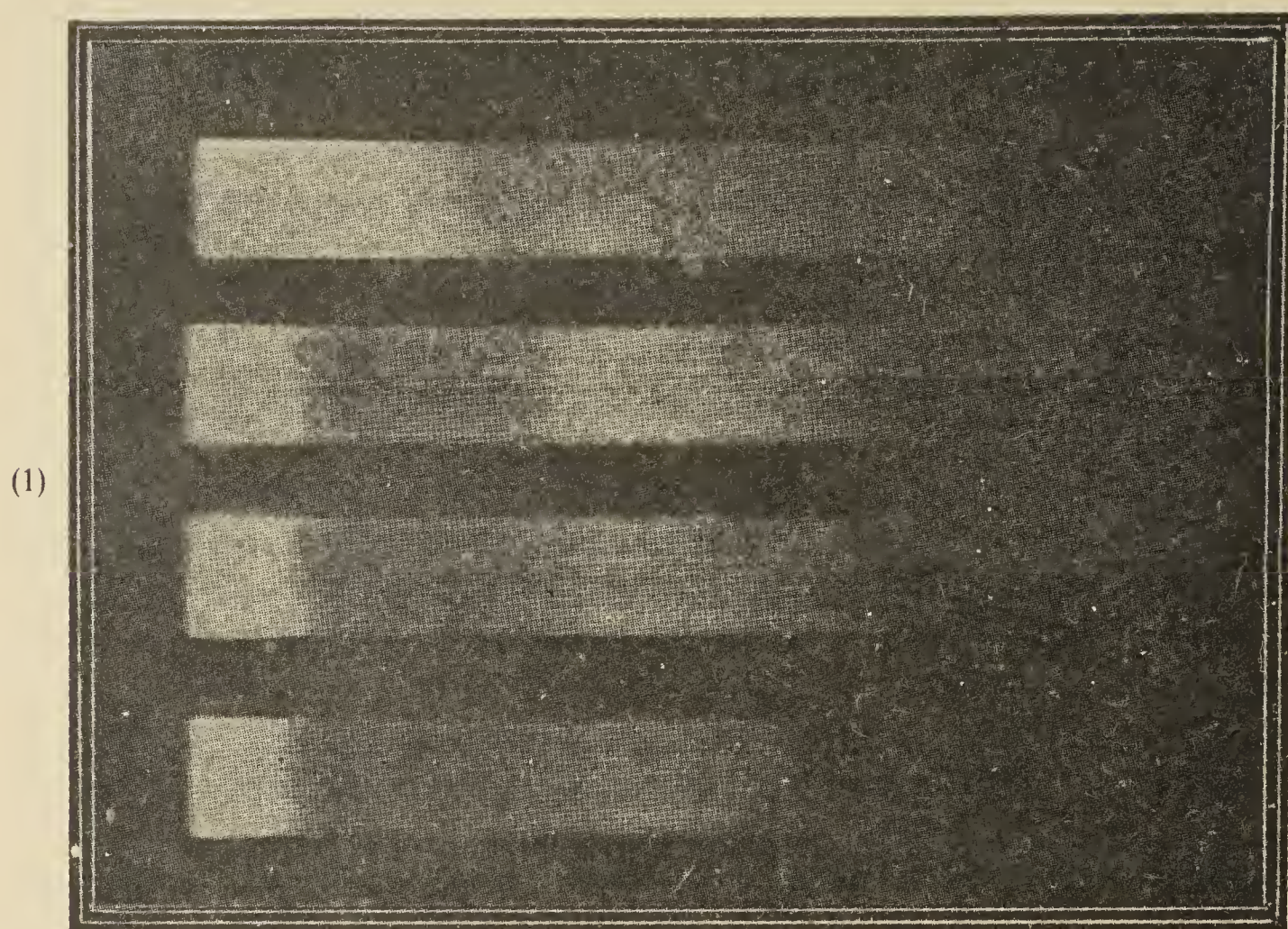


Figure 1 and 2. 1. Absorption spectra of purple balsam (with comparison spectrum) 2. Absorption spectra of red rose (with comparison spectrum).

That this did not result in the flowers appearing of a purple colour is due to the fact that in each case, an additional absorption band was noticeable which diminished the observable intensity in the orange-red parts of the spectrum.

Of particular significance is the behaviour of the flowers of the climbing creeper known botanically as *Ipomea learii* and popularly as the "Morning Glory". The absorption of this flower appears in a restricted region of the spectrum, the wavelength region between 560 and 590 $m\mu$ having a distinctly lowered intensity, while the region between 590 and 630 $m\mu$ is strongly absorbed. In other words, the yellow and orange sectors of the spectrum are partly or wholly eliminated, but the violet, blue, green and red sectors appear with undiminished intensity. That in these circumstances, the flower exhibits a deep blue colour without even a trace of any achromatic sensation being overlaid on it is quite remarkable.

Another interesting case is that of the tree *Solanum grandiflorum* popularly known as the large-flowered nightshade or potato tree. Spectroscopic examination reveals that its flowers exhibit an absorption band covering the yellow region of the spectrum. This is indeed a characteristic feature exhibited by all the blue flowers so far examined by the author. That the *Solanum* flowers exhibit a highly saturated bluish-violet colour instead of appearing as purple may be ascribed to the presence of an additional absorption band in the orange-red which diminished the observable intensity of that part of the spectrum.

From the facts set forth above, it is clear that the yellow sector of the spectrum covering the small wavelength range between 560 and 590 $m\mu$ plays an extraordinarily important role in the physiology of vision. Its presence in full strength, any reduction in its intensity, or its total extinction in the light from the object which reaches the observer's eye have enormous effects on the colour sensations experienced by him.

A detailed study has been made by the author of the origin of the characteristic green colour of vegetation. The usual explanation given of it is that the absorbing pigments present in green leaves eliminate the blue as well as the red parts of the spectrum, leaving us with the green, thereby accounting for the observed colour. Spectroscopic examination of the light which filters through green leaves shows this explanation to be untenable. The shorter wavelengths in the spectrum are indeed eliminated in the passage of light through a leaf, the carotenoid pigments playing the leading role in this respect. This is evident from the appearance of a fairly well-defined absorption limit at about 510 $m\mu$. On the other hand, the characteristic absorption bands of the chlorophyll pigments appear at the red end of the spectrum. The contribution of the extreme red to visual luminosity is quite small. Hence the absorption by the chlorophylls in that region can have no sensible effect on the observed colour of green leaves. Actually, the entire spectrum between the wavelength limits 510 and 650 $m\mu$, is transmitted. Hence, according to the ideas current at the present time, even a mature green leaf should appear of a golden yellow hue and not a bright green or a dark green as is actually the case.

The green colour of leaves thus confronts us with a basic problem in the physiology of vision. The clue to its solution is furnished by the fact that there is an observable diminution in the intensity of the yellow sector of the spectrum between 570 and 590 $m\mu$ in its passage through the leaf. This diminution is just noticeable in the case of tender leaves exhibiting a green colour tinged with yellow. It is easily seen with mature leaves which appear of a full green hue, while the absorption in that region is almost complete in the case of leaves exhibiting a dark green colour. It is clear that it is this absorption which determines the observed colour of the leaf. The rest of the spectrum between 590 and 650 $m\mu$ which passes through the leaf and can be seen through a spectroscope appears to have no effect on the perceived colour of the green leaf.

The present communication is essentially a recital of facts. It is evident that these facts are irreconcilable with the idea that the colour sensations produced by polychromatic radiation can be computed by arithmetic or algebraic processes involving only additions or subtractions. It is clear also that they require an alternative approach in which the concept is introduced of the masking in certain circumstances of the sensations produced by one part of the spectrum by those produced by another part. With the aid of that concept, it becomes possible to understand why a flower may appear of a full red colour but that it nevertheless transmits blue light freely, or why again, a leaf appears green despite the fact that a great deal of red light passes through it unabsorbed. But we shall not enter here into any detailed discussion of these interpretations of the observed facts.

The green colour of vegetation

SIR C V RAMAN

The blue of the sky and the green of vegetation are the colours exhibited by the face of nature with which we are all most familiar, one due to the atmosphere of the earth lit up by the rays of the sun and the other to the leaves of plants growing under the beneficent influence of those same rays. Like the colours of the sky, the colours of vegetation show a great range of variation alike in respect of their luminosity and their hue. They are of the deepest interest to us, for they are the symbols of life on the surface of our planet without which it would be a dead world. Quite naturally, therefore, the origin of those colours might well be expected to be a thoroughly understood subject. Remarkably enough, this is not so and it might justly be said that the reason why grass looks green to us is far from being familiar knowledge.

Even the thinnest of leaves when held up in sunlight does not permit of the sun's disk being seen through it. In other words, the incident light is completely diffused or scattered besides suffering absorption within the material. It is very commonly the case that the upper and lower surfaces of a leaf present a very different appearance. The former exhibit in diffuse daylight a deeper colour and are also smoother. In consequence, when held at the proper angle to a beam of light incident on it, there is an observable reflection or glitter at the surface. On the other hand, the colour of the lower surface appears diluted by admixture with white light and by reason of its roughness, the regular reflection by the surface is weakened and may indeed not be noticeable at all. In the circumstances stated above, we have two distinct and alternative methods of studying the colour of green leaves. The first is to observe the *upper* surface of the leaf holding it towards the light in such position and viewing it at such an angle that the surface reflection or glitter is unobservable and only the light emerging from the interior of the leaf is seen. The second method is to observe the light which emerges *through* the leaf when it is held up against the source of light. In the latter case, the slit of the observing spectroscope may be brought up close to the leaf. It then makes no difference which side of the leaf faces the source of light. In either case, it is desirable to use a powerful source of illumination.

It has long been known that the pigments universally present in green leaves are of two sorts and their chemical constitution has been ascertained by appropriate methods of investigation. They are respectively the carotenoids and the chlorophylls. When sunlight falls upon a leaf and before it can emerge again

from its interior, it suffers both diffusion and absorption. It is the remnant that survives these processes which we perceive, though it should not be forgotten that in many cases, reflection and diffusion at the exterior surfaces of leaves also play an important role in determining their appearance to an observer. If we lay aside the latter complication, we may say that the perceived colour is determined principally by the extinction of the sun's rays in their passage through the material of the leaf produced by the pigments referred to above. It is well known also that the carotenoids exercise a powerful absorption of the blue and violet regions of the spectrum. Such absorption is amply sufficient to account for the fact that very little of the wavelength range between 400 and 500 $m\mu$ gets through a green leaf, as may be readily verified by holding it up against the bright sky and viewing the light which filters through with a pocket spectroscope. Even with tender leaves which exhibit a greenish-yellow hue, the blue and violet of the spectrum come through only feebly, while in the case of the thicker and more mature leaves which appear of a full green colour, the extinction of the violet and blue is complete and extends also into the green up to 520 $m\mu$. The two species of chlorophyll respectively labelled as (*a*) and (*b*) which are present in green leaves exhibit a powerful absorption in the vicinity of the red end of the spectrum, the peak of chlorophyll (*a*), according to the observations which have been made with the material in an ether solution, appearing at about 660 $m\mu$ and that of chlorophyll (*b*) at about 640 $m\mu$. By holding up a green leaf against direct sunlight, and viewing the light emerging through it with a pocket spectroscope, it is possible to observe the absorption bands due to the chlorophylls appearing in the extreme red.

When we seek to understand or explain the colour of green leaves observed in these circumstances, it is necessary to remember that the luminous efficiency of monochromatic light varies enormously over the range of the visible spectrum. It is very small near the violet end of the spectrum, rises progressively and reaches a maximum at about 560 $m\mu$ and then drops down again at longer wavelengths. At 640 $m\mu$, it is only about 20% of its value at 560 $m\mu$, while at 660 $m\mu$, it is only about 10% and at 680 $m\mu$, it is very small. It is clear from these figures that the major chlorophyll absorptions appear in a region of which the luminous efficiency is already small. It follows that they could have no great influence on the visually perceived effect of the light that comes through, either in respect of the luminosity or in respect of its hue. It is known also that chlorophylls have a powerful absorption in the wavelength range between 400 and 500 $m\mu$. But this is the range in which the absorption by the carotenoids is also effective. The effect of the chlorophylls would therefore merge into it and need not be separately considered in the present context.

Thus, the observed colour of a leaf would be determined by its spectroscopic behaviour in the wavelength range between 500 and 640 $m\mu$ in which region neither the carotenoids nor the chlorophylls have any major absorptive effects. What the colour exhibited to our vision by this range of wavelengths would be—

in the absence of any specified absorption within that range—can be readily ascertained in a variety of ways. We may, for instance, simply view the sky through a colour filter which cuts out the whole of the spectrum up to $520\text{ m}\mu$ and lets through all greater wavelengths. The light transmitted by such a filter appears of a golden-yellow hue. There are several alternative procedures which yield the same observable result, viz., a golden-yellow colour. For example, we may use the petals of any flower which exhibits that hue and find that the light which filters through it has the same or nearly the same spectral composition. Many croton leaves exhibit (at least in some areas) a golden-yellow hue. Likewise, green leaves which have passed the stage of maturity and are about to drop off the tree usually exhibit a golden-yellow colour. Any of these cases can serve as a standard of comparison with the spectrum of green leaves in various stages of maturity.

When such comparisons are made, a surprising result emerges, viz., that the spectrum of the light emerging through a green leaf bears a close resemblance to that observed in the transmission through a flower or a leaf exhibiting a golden-yellow hue. Indeed, at first sight, it is not easy to discover what the difference in spectral composition are which give rise to the observed differences in the perceived colour. A critical examination of the transmission spectra of leaves in various stages of maturity however discloses that in the spectrum of the green leaf, the yellow sector of the spectrum between 570 and $590\text{ m}\mu$ is weakened. The weakening is just discernible with immature leaves which exhibit a greenish-yellow hue. It is easily seen in the case of mature leaves which exhibit a bright green colour. Leaves whose colour is a dark green show the absorption band between 570 and $590\text{ m}\mu$ conspicuously, the green and orange-red sectors of the spectrum which lie on either side then appearing well separated from each other. As we proceed from stage to stage in the development of the leaf towards maturity, the total quantity of light which finds its way through the leaf also progressively diminishes. Both the green and the orange-red sectors of the spectrum, however, continue to be visible with comparable intensities. But the intensity of the orange-red sectors relatively to that of the green sector shows an observable and progressive diminution.

From these observations, it becomes clear that the colour differences observed between a green leaf and a golden-yellow flower are the result of the absorption of the yellow sector of the spectrum between 570 and $590\text{ m}\mu$ in the green leaf. As this absorption progressively increases, the colour changes from a greenish-yellow to a bright green and finally to a dark green. Further, since the orange-red sector of the spectrum is conspicuously visible even in the case of mature green leaves whose colour does not exhibit the slightest hint of any yellowish tinge, we are obliged to conclude that as the yellow sector between 570 and $590\text{ m}\mu$ which is the connecting link between the green and the orange-red sector is weakened, the effect of the orange-red is masked or suppressed, in other words, prevented from entering into the range of perception, by reason of the presence of the more luminous green sector.

Owing to the non-uniformity of the photographic sensitivity of the commercially available panchromatic films in the region of the spectrum with which we are here concerned, it is not easy to obtain and present an objective demonstration of the facts of observation described above in the form of recorded spectra. After some discouraging failures, however, a fair measure of success has been achieved using the special "Agfa Raman plates" which have been developed by a well known firm of manufacturers.

Five spectrograms appear in figure 1 here reproduced. Of these, the second and the fourth, figure 1(b) and (d), are the spectra of the light source employed when covered with a golden-yellow filter. In these pictures, the left half of the spectrum

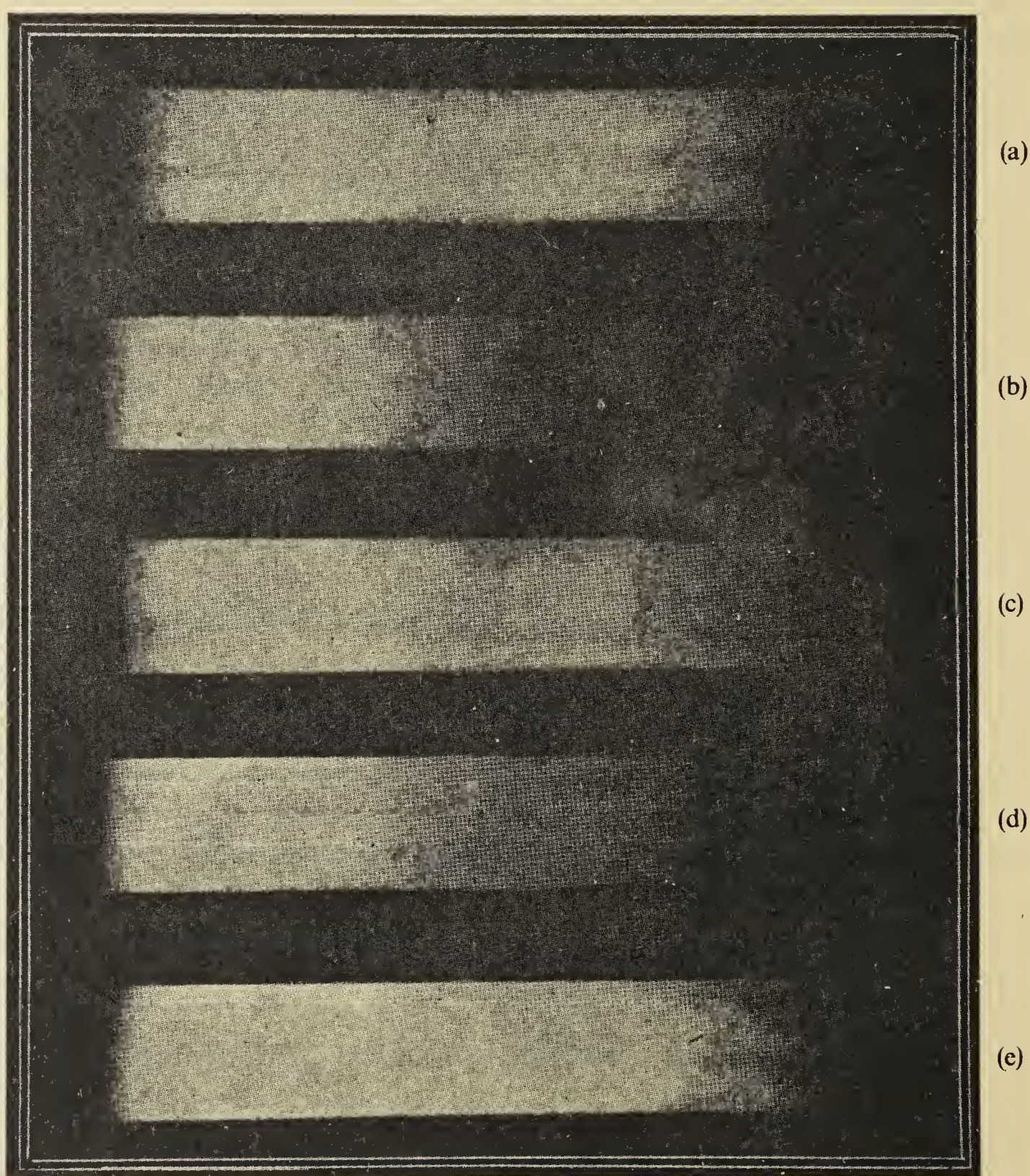


Figure 1. Spectroscopic comparison of green leaves and a yellow colour-filter. (a), (c) and (e), Green leaves; (b) and (d), colour-filter.

exhibiting the red and orange sectors appears much brighter than the right half which is the green sector. This is due to the difference in photographic sensitivity for these regions. It does not, however, prevent the effect under consideration, viz., the absorption in the yellow by the green leaves being exhibited in three other spectrograms, viz., figure 1(a), (c) and (e). They were recorded with three croton leaves, which were respectively a very dark green, a bright green and a greenish-yellow in colour. Figure 1(a) exhibits the absorption band in the yellow quite clearly. But it is much less clear in figure 1(c) and can scarcely be made out in figure 1(e).

Figure 1 also exhibits the other effects mentioned. In all the three cases studied, the red and the orange parts of the spectrum come through and their intensities are seen to be comparable with those of the green sector. We should, however, take note of the difference in photographic sensitivities for these regions. When due allowance is made for this, it is seen that the red-orange sector is weaker relatively to the green in the darker-coloured leaves.

We may sum up the results of the study by the statement that it is the absorption of the *yellow* of the spectrum and not the absorption of the red that is responsible for the observed green colour of leaves. That the absorption band in the yellow is not noticeable in the case of leaves which have turned yellow before dropping off is an indication that chlorophyll is responsible for its presence, either by itself or in association with the carotenoid pigments.

The extraordinary role played by the yellow sector of the spectrum in the case of the green leaves does not stand by itself. Indeed, in a forthcoming memoir by the author which will shortly appear in the *Proceedings of the Indian Academy of Sciences*, it is shown to be a very general feature. That the masking of the weaker by a stronger sensation is also a general feature has been recorded in that memoir.

The visual pigments and their location in the retina

SIR C V RAMAN

The faculty of perceiving light and colour which is one of our most precious possessions and plays an immensely important role in our lives is made possible by the marvellously organised structure of the retina and its connections with the cerebral centres. It is not surprising, therefore, that the details of that structure have been the subject of innumerable researches in the past. It is appropriate that we commence the present communication by briefly recalling those features of the retinal structure which have a bearing on the subject which will be dealt with here.

The retina may be described as an outlying part of the central nervous system to which it is connected by a tract of nerve fibres, namely the optic nerve. The nervous structure is encased within two coats which serve the purposes of protection and nutrition. Externally, we have the fibrous tunic which is white and opaque, namely, the sclera. Between this and the retina is a layer of which the function is primarily nutrient. This is known as the choroid and is a tissue almost entirely composed of blood vessels. Behind this again lies the retina which functions as the organ for the reception of visual impressions.

The retina itself is a multi-layered structure. The two innermost layers adjoining the choroid coat are respectively the pigment epithelium and the layer of rods and cones. These latter are recognized as the visual receptors. The two outermost layers of the retina are the so-called inner limiting membrane and the layer containing the optic nerve fibres. Between these two sets of layers appears an elaborate organisation of connective cells, pictures of which will be found in the anatomical treatises.

The area of the retina can be usefully divided into two parts, a central region measuring five to six mm in diameter and the peripheral part which is a much larger area surrounding it. An important part of the central retina is the area known as the *fovea*. This is a shallow rounded pit of which the diameter is about 1.5 mm. At the bottom of this pit is the area known as the foveola which is about 0.3 mm across. The depression of the fovea below the general level is due to the practical disappearance of the inner layers of the retina, compensated somewhat by the increased thickness of the layers containing the rods and cones. Outside the fovea and in the central retina, two further regions have been recognized and distinguished from each other on morphological grounds, namely the *parafovea*

which is a belt 0.5 mm wide all round the fovea, and a second belt known as the *perifovea* which is about 1.5 mm across.

It is well known that the *fovea* plays a highly significant role in human vision. It is the region of the retina on which the image of any object falls towards which we direct our vision. When the fundus of the living eye is viewed through an ophthalmoscope, the fovea can be glimpsed at the centre of the region of the retina known as the macular area. The fovea is seen somewhat more conspicuously with the ophthalmoscope when the fundus is viewed in red-free light, it being then visible as a spot of yellowish hue surrounded by a greenish-yellow field. This effect arises from the presence of a yellow pigment in the macular area which permeates diffusely the retinal tissues from the outer nuclear layers inwards.

The present communication is concerned with the visual perception of colour and the part played by the retina in such perception. It is useful here to recall the basic facts of the subject. The visible spectrum is comprised in the wavelength range between 400 and 700 $m\mu$, the perceived colour altering continuously from one end of the range to the other. It may be demarcated into six regions, designated as violet, blue, green, yellow, orange and red respectively; the limits between them are indicated in figure 1 by broken vertical lines whose positions have been taken as 436, 495, 566 and 627 $m\mu$ respectively. The luminous efficiency of visible radiation reaches very low values at either extremity of the range. Intermediately, as shown in figure 1, it reaches a maximum at 560 $m\mu$, in other

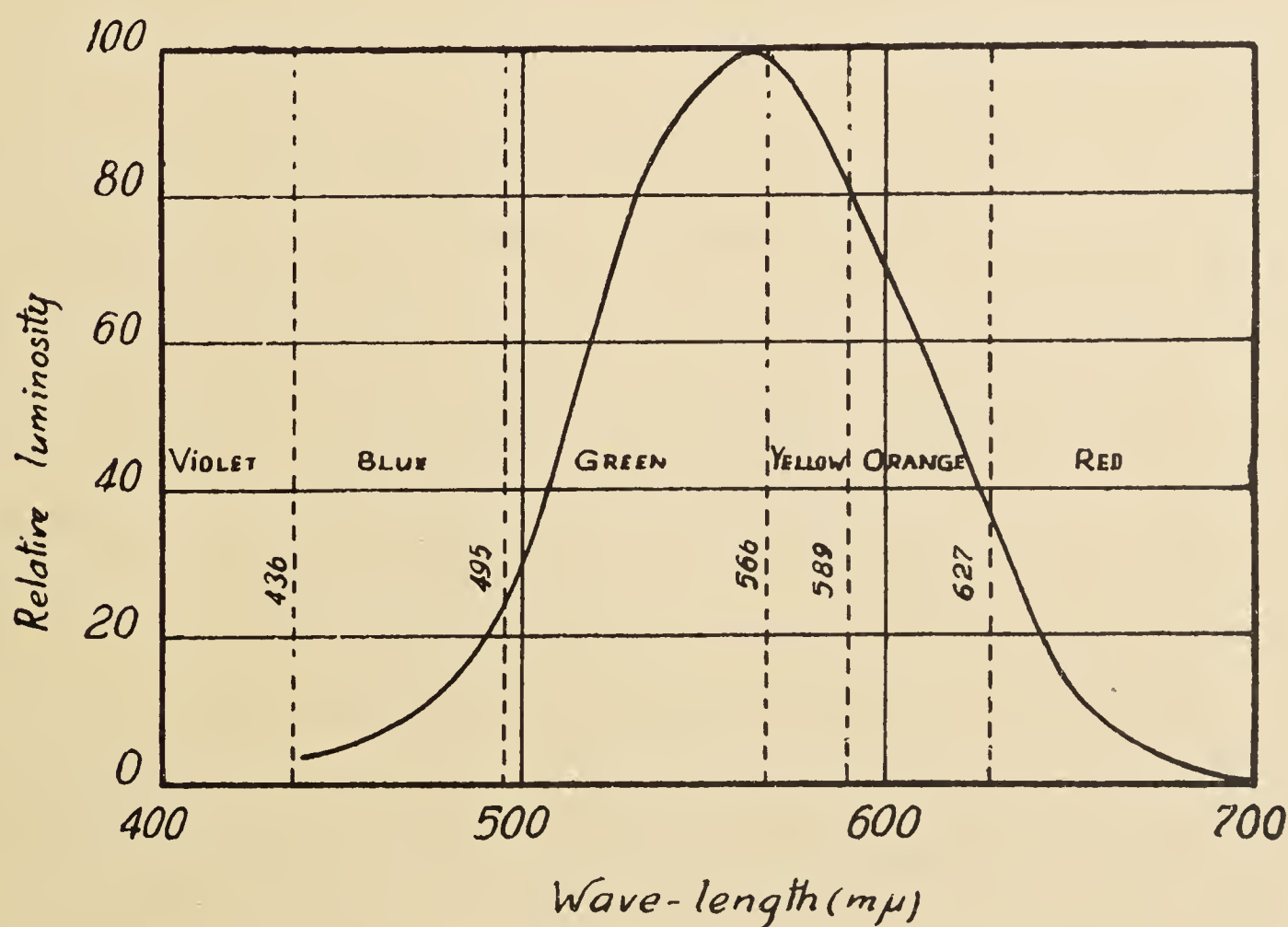


Figure 1. Luminous efficiency of the visible spectrum.

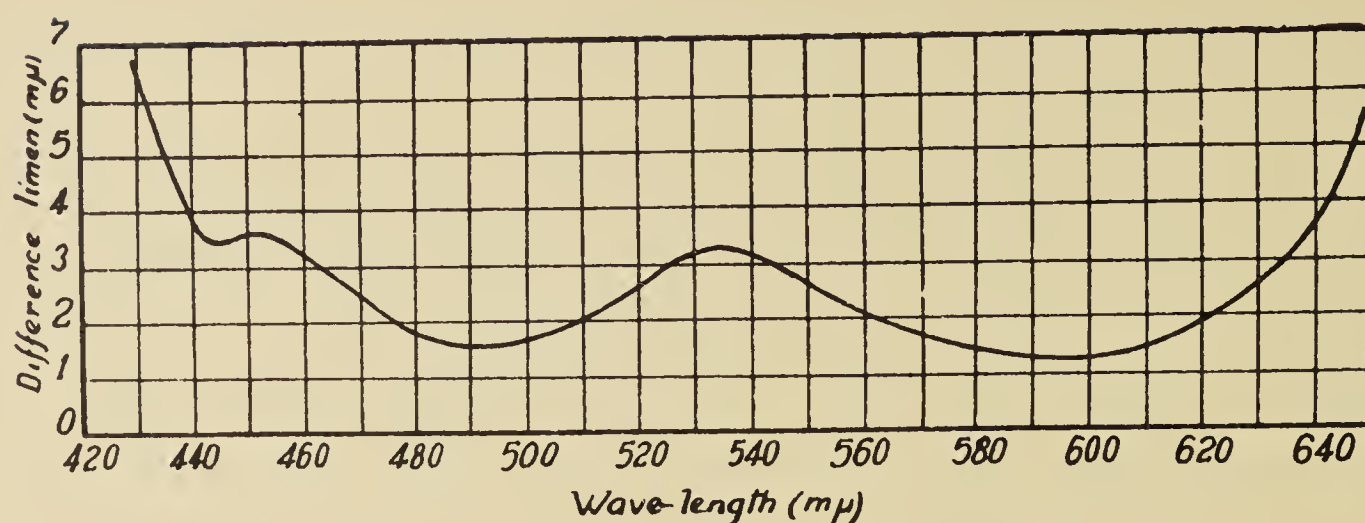


Figure 2. Hue discrimination in the spectrum.

words not far from the boundary between the green and yellow sectors of the spectrum. The most rapid increase of the luminous efficiency as we move towards greater wavelengths appears at about 520 mμ and the most rapid fall at about 590 mμ.

Figure 2 shows the hue discrimination curve, in other words, the smallest change in wavelength which manifests itself in vision as a perceptible change of colour in various regions of the spectrum. It will be noticed that except near the ends of the spectrum, a change of 4 mμ is more than sufficient to produce an observable change of hue. Indeed, over the greater part of the spectrum, the power of colour discrimination is much greater. Dips in the curve appear at 444, 492 and 595 mμ, these wavelengths being nearly the same as those at which the observed colour changes from violet to blue, from blue to green and from yellow to orange respectively.

The present communication records the results obtained and the conclusions reached from a study of the functioning of the retina in its central region in terms of colour sensitivity. The method of investigation is that devised by the author and described in earlier publications by him, but it has now been much improved by reason of the attention paid to important details of the technique. The method of observation makes use of a set of colour filters so chosen or prepared that they are more or less completely opaque to a limited region of the visible spectrum but transmit other parts of the spectrum freely without any sensible absorption. Holding such a filter in front of his eye, the observer views a brightly illuminated white screen, fixing his vision at some particular point on the screen and after a short interval of time, varying from a few seconds to a few minutes according to the circumstances of the case, suddenly removes the filter from before his eye. He then observes on the screen an enlarged picture of his own retina, the nature of which varies with the filter used. From the nature of the picture seen, the spectral sensitivity of the retina and its variations over its central region, and especially the dependence of such sensitivity on the choice of the spectral region may be inferred.

How the effects observed in this manner with the aid of the colour filters arise is

an important question regarding which some remarks of a preliminary nature may be made here. It is evident that if the colour filter cuts off a limited part of the spectrum, in the light which reaches the observer's eye through the filter that part of the spectrum would be missing, and hence it would also be missing in the light falling on the retina. The interval of time during which the observer views the screen through the filter is much too short for any retinal fatigue to be produced by the parts of the spectrum transmitted by the filter. *But it may suffice to enhance the sensitivity of the retina to the parts of the spectrum cut off by the filter.* The extent of such enhancement may be expected to depend on the circumstances of the case, viz., the part of the spectrum screened off by the filter, the state of adaptation of the retina to light before the filter is put in, the illumination of the screen which is viewed and finally the duration of time for which the filter is held in front of the eye before it is removed.

In the earlier studies by the author, the colour filters employed were gelatine films on glass stained to the desired extent. While there is much to be said in favour of such filters, it has been found desirable in critical studies to use instead, aqueous solutions of various dye-stuffs contained in glass cells, 10 by 10 cm² in area and 2.5 cm in depth, which is then the effective absorption path. The advantage of using such cells is that the filter may be quickly prepared by dissolving a little of the dye-stuff in distilled water, and then by diluting the solution to the desired extent. The spectrum of the light transmitted by such a filter may be observed at different dilutions and the state of dilution may be adjusted suitably. This procedure is very helpful, since strong solutions of the dye-stuffs used absorb extensive regions of the spectrum, but when sufficiently dilute the region of cut-off is greatly restricted and may indeed then be confined to the specific absorption bands characteristic of the dyestuff.

Amongst the dye-stuffs which had been employed in the present investigation may be mentioned the following, the names being those under which they are commercially available: (1) Acridine orange, (2) Eosine, (3) Rhodamine, (4) Coomassie brilliant blue, (5) Methyl violet and (6) Lissamine green. Of particular importance are the observations made with solutions of these dye-stuffs of such dilution that the absorption is strong or nearly total in a limited region of the spectrum, while the rest of the spectrum is freely transmitted. Using this technique, the entire spectrum may be surveyed in detail. It emerges that it divides itself according to the observed results into five distinct regions: (1) 400–495 m μ , (2) 495–540 m μ , (3) 540–560 m μ , (4) 560–590 m μ , and (5) 590–700 m μ . Absorption only in the first of these regions may be obtained with appropriately diluted solutions of acridine orange. Absorption appearing only in the second region may be obtained with very dilute solutions of eosine; an absorption appearing only in the third and fourth regions with dilute solutions of Coomassie brilliant blue or methyl violet and in the fifth region alone with very dilute solutions of lissamine green.

The experimental results may be briefly summarised as follows. Working in the

first region which comprises the blue-violet parts of the spectrum, the observer notices on the screen following the removal of the filter, a blue glow covering the entire area of the screen. In the second region, namely $495-540\text{ m}\mu$ no effect of any kind is noticeable, since on the removal of the filter, the observer sees the white screen as before. In the fifth region, namely $590-700\text{ m}\mu$, following the removal of the filter the observer sees a rose-red glow covering the entire screen. Using filters whose absorption is effective in the third and fourth regions, in other words between 540 and $560\text{ m}\mu$ and between 560 and $590\text{ m}\mu$, very striking effects which reveal the structure of the retina are observed. The actual picture of the retina seen by the observer with such filters exhibits colours depending on the part of the spectrum which is cut off or weakened by the filter. But its general configuration is sufficiently well illustrated by the drawing in black and white reproduced as figure 3.

Four distinct areas appear in figure 3, whose correspondence with the different parts of the central retina may be checked by actual measurement of the angular dimensions of these features as seen on the observing screen. Around the point on the screen at which the observer's vision is fixed appears the foveal disk (enormously magnified) with the central pit or foveola and the umbo or navel very distinctly noticeable therein. Surrounding the fovea is seen a third region which appears encircled by a distinct halo along its margin. Outside this appears a fourth region without any distinct outer limits defining its extension. In general,

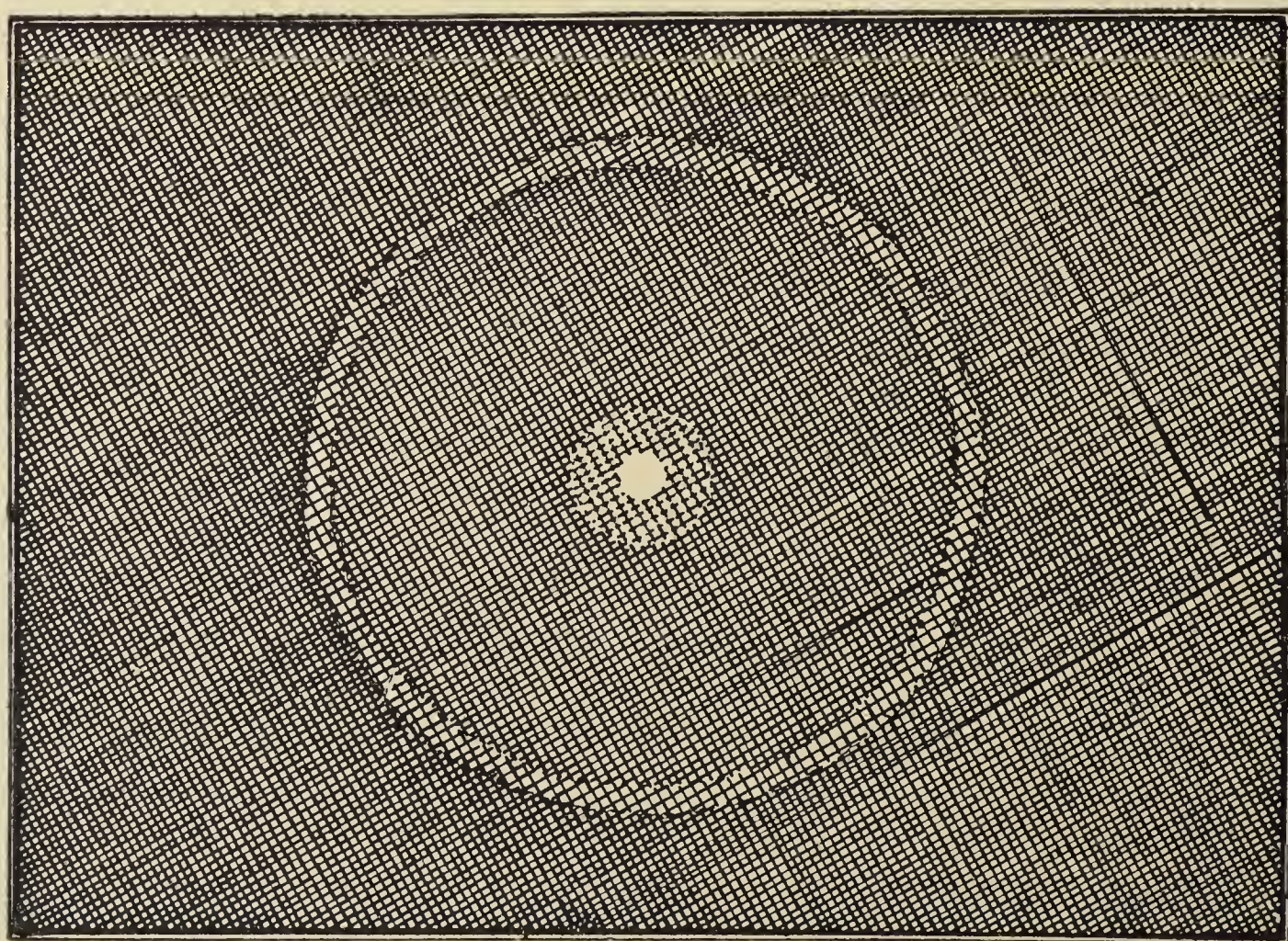


Figure 3. The retinal picture seen with colour filters.

by far the most luminous part of the picture is the fovea and this also exhibits vivid colour. The parafoveal and perifoveal regions are less luminous and distinctly less colourful.

Observations made with solutions of Coomassie blue, methyl violet and lissamine green in different states of dilution make it evident that the retinal picture seen with the filter technique is different in the two cases where the absorption by the filter appears respectively in the third and fourth spectral ranges, viz., 540–560 $m\mu$ and 560–590 $m\mu$. In the third range, the fovea appears as a disc of a green hue and the perifovea also appears of the same colour. When the absorption is in the fourth range, the fovea is seen as of a bright yellow colour and the perifovea is likewise of that hue though less brilliant.

We may now proceed to consider what the observations described above signify in relation to the role played by the retina in the perception of colour. The effects observed are of a transitory nature in every case, but they differ enormously in the different parts of the spectrum. These differences are evidently connected with the variations in the luminous efficiency of radiation in the different parts of the spectrum. In the blue-violet and in the red regions of the spectrum, the effect observed following the removal of the filter is a glow covering the entire screen. It is noteworthy that for such an effect to be observed, it is necessary to hold the filter for an appreciably longer period in front of the eye. It may therefore be reasonably explained as due to the sensitisation of the retina for the wavelengths absorbed by the filter by its screening effect. On the other hand, the luminous efficiency of the spectrum is fairly high in the region between 495 and 540 $m\mu$ and it is not surprising, therefore, that no effect at all is observed when the filter which has an absorption in this region is put in front of the eye and then removed.

We may now proceed to consider the explanation of the effects pictured in figure 3. They appear only when the colour filters used have absorptions in the wavelength range lying between 540 and 590 $m\mu$. This spectral range is precisely that where the luminous efficiency of the spectrum is highest. It follows that the origin of these effects is quite different from those of the effects observed in the blue-violet and red regions of the spectrum which have very low luminous efficiencies. That the character of the effects is very different is also not surprising.

A reasonable explanation for the effects pictured in figure 3 appears to be that the visual pigment functioning in the spectral region between 540 and 590 $m\mu$ is not identical with those functioning in the blue-violet, green or red sectors of the spectrum and that it is distributed in a highly non-uniform manner over the central part of the retina, being concentrated in the foveal area and in the regions immediately surrounding it. Following the removal of the filter, the regions of the retina containing the pigment under reference are lit up and flash into view. Such an effect can, of course, only be transitory. But it is worthy of note that it is restored in full strength when the filter is quickly put back and then again suddenly removed. The same procedure may be repeated as often as desired,

thereby enabling the details of the retinal picture to be carefully studied. We are justified by these facts in inferring that what is actually perceived is a picture of the distribution of the visual pigment over the area of the retina under examination exhibiting the part of the spectrum incident on it and in which it functions as a receptor.

It thus emerges from the present investigation that the visual pigment which functions in the yellow sector of the spectrum and is responsible for the very high luminous efficiency and the very high power of colour discrimination indicated by figures 1 and 2 for that part of the spectrum is quite distinct from the pigments which function in the red and green sectors of the spectrum and is not a mere superposition of these two pigments functioning jointly. The identification of that pigment presents a problem which will not be discussed here. But a useful hint is furnished by the observations which indicate that the pigment has *two* maxima of absorption, one between 540 and 560 $m\mu$, another between 560 and 590 $m\mu$, the latter being much the more pronounced of the two. Incidentally, it may also be remarked that the concept of three visual pigments or three fundamental sensations which forms the core of the Young-Helmholtz theory of vision is contradicted by the results of the present study and is therefore unsustainable.

The colours of gemstones

SIR C V RAMAN

Colour is the sensation experienced by an observer when he views the material under study. It is, therefore, essentially a subjective phenomenon. While the optical properties of the material alter the spectral character of the light falling thereon and emerging therefrom which reaches the eye of the observer, the visual impression which such light produces is determined by the physiological characteristics of the sensory apparatus. These characteristics accordingly play the leading role in the perception of colour and must necessarily take precedence in all considerations regarding the subject.

In a memoir by the writer which has been recently published (reference 1), the results of systematic studies on floral colours have been described and discussed. The products of the plant world, including especially the leaves and flowers of living plants, constitute a very large class of materials exhibiting colour which invite study. Being products of biological activity, they conform to set patterns and are therefore exceptionally well suited for precise scientific investigations. The number of species of flowering plants is enormous, and the colours displayed by their flowers are of the most varied nature. Further, not merely is the material available in abundance, but it is also available in forms and sizes exceptionally well suited for a spectroscopic examination. It is only to be expected in these circumstances that the studies would be richly rewarding and this has indeed proved to be the case. The observational data which the studies have yielded are of a comprehensive nature and have been obtained by methods which do not involve any particular assumptions or hypotheses regarding the visual mechanism and what it is or is not capable of achieving. In other words, they represent the results of an unbiased study of the facts and therefore give us a true picture of the reality.

It emerges clearly from the studies on floral colours that the ideas regarding colour composition and colour perception based on the so-called trichromatic hypothesis are inadmissible and have of necessity to be totally rejected as being inconsistent with or contradicted by the real facts of the case. As an example of such inconsistencies and contradictions, we may mention here the circumstances in which the well-known sensation of "purple" is actually perceived. Numerous flowers exhibit that colour, and spectroscopic examination reveals that it arises from the more or less complete extinction of the narrow range of wavelengths between 560 and 590 $m\mu$ which constitutes the yellow sector of the spectrum, all

other parts of the spectrum remaining unaffected. This result, even taken by itself, is a complete refutation of the entire framework of ideas embodied in the so-called trichromatic hypothesis.

Another class of objects which exhibit colour and are worthy of study form the subject of the present communication, namely gemstones. In several respects, they are an antithesis to the products of the plant world when considered from the present point of view. For a material to be classed as a gemstone, it must be a rarity or at least so scarce as to be an expensive commodity, usually available only in small pieces and generally only after it has been converted by lapidaries into a form calculated to exhibit its lustre and beauty to the maximum extent and for that same reason wholly unsuitable for any precise scientific investigation of its spectroscopic behaviour. It is the rarity and costliness of the gems which are natural products which motivated the efforts made to produce them synthetically, thereby creating for buyers and sellers alike, the acute problem of distinguishing between the natural and synthetic gemstones. Nevertheless, such questions, as for example, why is emerald green, why is ruby red and why is sapphire blue, possess both a human and a scientific interest. One can, of course, escape the difficulty of obtaining material suitable for the studies by employing the synthetic instead of the natural gems. But, then, the interest of the investigation and of its results would be materially diminished.

To the reader interested in gemstones and the practical problems arising in the identification of gemstones and of distinguishing between natural and the synthetic gems, Mr B W Anderson's book on gem-testing (6th Edition, Heywood and Co., London) may be heartily recommended. The following remarks made by him which are pertinent to the subject may usefully be quoted here: "Minerals can be classified into the idiochromatic ('self-coloured') type which owes its colour to an element which is an essential part of its composition—e.g., the iron in almandine garnet or peridot, the copper in malachite—and the allochromatic type, in which the colouring element is present in quite small quantity as an 'accidental' impurity. The majority of gem minerals are allochromatic: that is, the mineral itself has no distinctive colour, and is in fact colourless when pure, but exhibits a range of coloured varieties according to the presence of traces of different colouring elements. Quartz, beryl, corundum, tourmaline, topaz, spinel, zircon, and many others are in this category."

Anderson's book also contains a chapter on the use of the spectroscope in gem-testing which contains material relevant to the present topic, viz., the colours of gemstones. In that chapter are reproduced four charts which contain drawings made from visual observations of the spectra of 35 different gemstones, grouped together under the four headings of red, yellow, green and blue stones. The spectra exhibit very varied features, and this fact is of considerable assistance in the identification of the gemstones. The usefulness of the charts from this point of view should not however be allowed to obscure the fact that they cannot serve as a basis for the explanation of the colours of the gemstones. It is not merely the

positions of the absorptions noticeable in the spectrum of the gemstones, but also the strength of such absorptions that has to be considered in relation to the intensity of the unabsorbed parts. In other words, we need a complete picture of the energy distribution or at least of the visual luminosities in the spectrum of the light emerging through the gemstone before we can proceed to consider the explanation of its visually observed colour.

It is naturally to be expected that the results which have emerged from the studies on floral colours would be found to be equally well applicable to the case of gemstones and enable us to give a satisfactory interpretation or explanation of their colours. The interest of the subject and the fact that a considerable collection of gem minerals was available in the museum of the Raman Research Institute induced the author to undertake some preliminary studies in this field with a view to find whether this is actually the case. The present communication is a brief report on the results.

We may first consider the case of emerald. The rich green colour characteristic of this gem is exhibited by numerous pieces of beryl purchased by the author some years ago at Jaipur in Rajputana and included in the collection of beryl specimens of various sorts deposited in his museum. Unfortunately, however, none of these specimens is transparent enough to permit of light transmitted in the regular fashion through it being observed or examined. However, the author was presented by Sri Chand Golecha, a leading jeweller of Jaipur, when he recently visited Bangalore, with a hexagonal crystal of beryl from the Colombian mines about one centimetre thick. The two faces of the plate facing each other were ground down and polished, and the material was then found to be fairly transparent and the transmitted light also exhibited the characteristic green colour of emerald. Visual spectroscopic examination, confirmed by photographically recorded spectra, showed that in the passage of light through the plate, the violet and blue sectors of the spectrum were noticeably weakened, especially the former. But there was a readily observable transmission in the wavelength range between 450 and 500 $m\mu$. The green and the red sectors of the spectrum were also visibly diminished in their intensities in the light emerging through the plate. But such diminution was not more than could reasonably be ascribed to the loss by reflection at the two surfaces of the plate as well as the imperfect transparency of the material. On the basis of these facts, we should have expected the colour of the light emerging through the emerald to be a bright yellow, while actually it was a clear green.

We have now to consider the explanation of this striking discrepancy. There is indeed a weakening of intensity (including a narrow band of absorption) noticeable at and near the red end of the spectrum. But the visual luminosity of this part of the spectrum is so small that such absorption is incapable of explaining the fact that the observed colour of the gem is green and not yellow. A careful examination of the spectrum shows, however, that the part of the spectrum between 570 and 600 $m\mu$, in other words, the yellow sector of the

spectrum is greatly weakened. It is clear that it is this extinction of the yellow that is responsible for the observed colour of emerald.

The results obtained with the hexagonal beryl crystal were confirmed with a fine piece of emerald of gem quality which was purchased from a jeweller at Bangalore. It is of much smaller thickness (about 2 mm), but exhibits a deep green colour. The yellow of the spectrum is found to be greatly weakened in the passage of the light through the gem. The aggregate intensity of the red sector relatively to the green sector is distinctly less than it is before entry into the gem, but it is far from being negligible. The observed vivid green hue of the emerald indicates that in the circumstances of the case, the visual sensation excited by the red sector is more or less completely masked by that of the more luminous green sector, in other words, prevented from influencing the perceived colour of the gem.

We shall next consider the case of the ruby. The author's collection of corundum from Ceylon includes numerous individual specimens exhibiting varied colours. Placing them under the ultra-violet lamp and picking out those which exhibit the characteristic red glow enables us to separate the rubies from other species of corundum. Such separation resulted in the interesting discovery that some rubies exhibit a purple colour. They show a strong absorption in the region of wavelengths between 560 and 590 m μ , in other words, of the yellow sector in the spectrum. Their spectral behaviour thus closely resembles that of the purple flowers mentioned earlier.

Rubies which appear red owe their colour to the existence of an absorption covering both the yellow and green sectors of the spectrum. It is a remarkable fact that the blue of the spectrum is transmitted more or less freely by such rubies. But it does not appear to influence the observed colour. We are led to infer that in the particular circumstances of the case, the weaker sensation due to the blue part of the spectrum is masked or prevented from being perceived by the more luminous red sector.

Flowers which appear of a blue colour invariably exhibit a strong absorption of the yellow of the spectrum. A very similar behaviour is found to be exhibited by blue sapphire.

We may sum up all that has been said above in a few words, viz., that the colours of gemstones exhibit features which are in complete accord with those met with in the realm of flowers (reference in footnote).

Visual acuity and its variations

SIR C V RAMAN

1. Introduction

Our visual organs are the principal gateways through which a knowledge of the external world finds its way into the realm of human consciousness and in consequence, they play a role of immense importance in human life and activity. Three distinct types of sensation are recognisable in the visual pictures of the outer world presented to us by our eyes, being respectively the binocular perception of space and form, the perception of colour and the perception of luminosity. These perceptions correspond respectively to the three physical characteristics of light considered as electromagnetic wave-motion in space which finds an entry into our eyes, viz., its rectilinear propagation in free space, the length of the waves and the magnitude of the electric-vector in them. The value of the information conveyed by our visual impressions depends greatly on their accuracy. The precision reached in each of the three types of sensation is therefore a highly significant feature of our visual perceptions. They are respectively the acuity of vision, the power of colour discrimination and the photo-sensitivity. These definitive characteristics of our subjective sensations are of great importance in all considerations regarding the *modus operandi* of the physiological perception of light.

Reference was made above to the properties of light regarded as electromagnetic wave-motion in space. But in considering the sensory perception of light following its incidence on the retinae of our eyes, these properties cease to be relevant, and we have, instead, to consider light in its quantum-theoretical aspects, in other words, as consisting of discrete quanta of energy. For, the absorption of light by the visual receptors is a necessary condition for its perception and such absorption takes place in complete quanta of energy. It follows that in seeking for an explanation of the various features characteristic of the visual perception of light, we have necessarily to proceed on the basis of the quantum theory. In particular, the acuity of vision, the power of colour discrimination and the sensitivity of our eyes to differences of intensity have all to be understood or interpreted on that basis. Though it is convenient to separate these three aspects of vision in describing and discussing the results of observation and experiment, they are, in reality, so closely inter related that we

have necessarily to adopt the same fundamental basis of approach for elucidation in all the three cases.

2. Colour and the quantum theory

The intimate relationship between the theory of light-quanta and the physiological effects of light becomes evident when we consider the sensations excited by the monochromatic rays of the spectrum. As we proceed from the red to the violet end of the spectrum, the magnitude of the energy-quantum in light increases progressively and continuously. Likewise, we perceive a continuous progression of colour, and there is thus a one-to-one correspondence between the perceived colour and the magnitude of the energy-quantum. We are, therefore, justified in regarding every one of the numerous distinguishable colours in the spectrum—of which there are some 150 or more—as primary or fundamental physiological sensations. The so-called trichromatic hypothesis which assumes that there are only three fundamental colours or only three fundamental sensations has, therefore, no logical basis and is unsustainable. The explanation of the known facts regarding the perception of monochromatic light—namely the variations of the luminous efficiency and the variations of the power of colour discrimination noticed as we proceed along the spectrum from end to end—is to be found in the specific characteristics of the absorbing materials which function as the receptors in the retina. We shall not here pause to discuss these matters further, but will pass on to consider the subject of the acuity of vision on the basis of the quantum theory. This subject is, indeed, the principal topic to be dealt with in the present communication.

3. The factors influencing visual acuity

In any discussion of the subject of visual acuity, we have to assume that the functioning of the dioptrics of the organs of vision is perfect. This, of course, is not necessarily always the case. But since the various possible defects in such functioning can be corrected more or less perfectly after ophthalmoscopic examination, they need not trouble us here. Chromatic aberration in the eye and its elimination by the use of monochromatic light are, however, not unimportant in the present context. The two factors which most notably influence visual acuity are, firstly, the region of the retina which is made use of, and secondly, the intensity of the illumination employed. Other factors are the spectral nature of the illumination, the distribution of light in the object under view and the illumination of the surrounding field. We shall here briefly recall some well-established facts regarding these matters.

When we wish to observe any object closely, we turn our eyes and

accommodate their focus so as to ensure that the image of the object falls precisely on the foveal region of the retinae of both eyes. It is well known that the visual acuity is highest when the region under observation falls precisely at the centre of the fovea and that it falls off with extreme rapidity when the image moves away from that position. A movement of 10° in either direction is sufficient to reduce visual acuity to 20% of its maximum value, while a displacement of 20° brings it down to 10% of the maximum. Beyond this again, the acuity for daylight vision continues to fall off, but more slowly.

The influence of the intensity of illumination on visual acuity is a matter of familiar experience. The acuity is highest at high illuminations and falls off, at first slowly, and then much more quickly, and becomes a small fraction of its maximum value when the illumination is weak, even when it is well within the photopic range. These changes in the acuity of vision with diminishing illumination becomes evident, for example, when we seek to read the pages of a printed book by daylight in the late hours of the afternoon when the sun is about to set and before it has actually become dark. The smaller the print, the greater is the difficulty felt in recognising the letters on the page.

The influence of the spectral nature of the illumination on acuity is, speaking broadly, of the nature which might be anticipated from the consideration that the luminous efficiency of radiation varies enormously as between different parts of the spectrum. The acuity is, in fact, found to be greatest in the part of the spectrum which has the highest luminosity, the order being yellow, orange, green, red and blue. It is particularly low at and near the blue end of the spectrum which has a very low intrinsic luminosity.

Since visual acuity usually depends on the perception of differences in the luminosity of adjoining areas in the field of vision, it naturally falls off as these differences diminish. Likewise, it has been found that for a given brightness of the test-object, the acuity improves as the surround illumination is increased, until the brightness of surround and test-object are equal. A further increase of surround illumination then causes a rapid fall in acuity.

4. The measurement of visual acuity

What precisely we mean by visual acuity depends on the nature of the object or objects under examination. It follows that there are several different ways in which the acuity may be defined and measured. One of the classic definitions is our ability to distinguish two stars in the night sky which are very close together as distinct objects. Amongst other tests may be mentioned, the discrimination of two parallel lines, the alignment of a vernier, the recognition of a break in a contour, the recognition of a localised thickening in the circumference of a circle, or the appearance of a crossed pair of gratings held together at various angles with respect to each other. Amongst other devices which have been employed

may be mentioned the broken circle of Landolt where a circle with a gap is presented and the observer is asked to say in what segment the gap lies.

A commercially available test-object for the study of the variations of visual acuity is the chart regularly used by ophthalmologists for detecting and correcting defects in vision. These charts are sets of letters arranged in a descending order of size. The observer sits at a convenient distance away from the chart (say 6 metres) and his vision is expressed as a fraction of this distance and the theoretical distance at which the letters should be read on the basis of a minimum visual angle of one minute of arc. Using such a chart, the changes in visual acuity manifesting themselves in normal vision when the illumination is varied can be readily observed and measured. In such measurements, three different procedures may be adopted. Keeping the illumination constant, the observer may note the effect of his gradually approaching the chart in making the smaller letters appear distinct. Alternatively, the observer remaining in the same position with respect to the chart, the power of the light source may be varied. The third procedure is for the source and the observer to remain in the same position and to move the chart away from them so that both the illumination of the chart and the angular dimensions of the letters progressively diminish. All three procedures yield comparable results.

5. The physiological bases of acuity

It is evident that for very fine detail of the object under observation to reveal itself to our perceptions, two conditions must be satisfied. Firstly, well-defined optical images of the object should be formed on the retinae of our eyes. Secondly, there should be present on the area of the retina where such images are formed, a sufficiently close-packed mosaic of receptor-elements that can receive the incident light-image and transmit the details thereof to the visual cortex. But there is also a *third* and highly important condition to be satisfied which emerges as a consequence of the constitution of light itself, viz., that it consists of discrete quanta of energy which must be absorbed as such by the visual receptors before the light can be perceived. We shall now consider each of these three conditions separately and comment on the influence exercised by them on visual acuity.

We have already referred to the first condition which should be satisfied for the highest acuity of vision to be possible. Even apart from any imperfections in the dioptric media of the eye, chromatic aberrations and the diffraction of light by reason of the limitation of aperture by the pupil of the eye have necessarily to be taken into account. The limitations set by these factors on visual acuity are well understood and we need not pause here to discuss them in detail. The fine structure of the retina, in other words, the size of the individual cones which are recognised as the receptors in daylight vision, and the manner which they are disposed relatively to each other determines the possibility of the details of the

retinal image being conveyed to the visual cortex and thereby find a place in the perceived image of the object. The nature of the connections between the retina and the visual cortex is an important factor in this respect. The evidence that has been found that individual nerve-fibres carry the nerve-impulses from the receiving cones to the sensorium makes it easier to understand how the observed acuity of vision is attained.

It is with the *third* factor influencing the acuity of vision with which we are here specially concerned. The observed diminution of the visual acuity which accompanies a fall in the illumination of the objects under study finds a natural explanation on the basis of the principles of the quantum falling on each element of area of the retina to put forward a rational explanation of the observed facts on any other basis. If the optical image formed on the retina is to be transmitted without loss of detail to the visual cortex, the number of quanta of energy falling on each element of area of the retina and actually absorbed by it and passed on to the visual centres in the brain should be such that each cone in the area under consideration can function fully and effectively. This would obviously not be possible if the flux of illumination falling on the retina is too small, or if the absorbing power of the retinal pigments is inadequate to capture all the incident light-quanta, and make them available for visual perception. The fact that photopic vision can adjust itself to very high levels of illumination is an indication that the visual pigments present in the retina are not capable of absorbing more than a very small percentage of the incident light quanta. If, in addition, the retinal illumination is itself of low intensity, not more than a small fraction of the cones in the retina can actually be functioning in any small interval of time—such as, say, one-hundredth part of the second—and a dropping off of the visual acuity to very low values is then inevitable. A simple calculation which takes account of the number of light-quanta incident on the retina during any such small interval of time and the number and spacing of the receptor-elements, viz., the cones present in the area shows that this explanation is sustainable.

Floral colours and the physiology of vision— Part I. Introductory

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The physiology of the sense-organs aims at bringing the physical and psychological aspects of sense-perception into an intelligible relationship with each other. In particular, the physiology of vision seeks to connect the physical nature and properties of light with the sensations which it excites in our visual organs. For this purpose, it is necessary at the very outset to recognise that light consists of discrete units or quanta of energy. For, the interplay of light and matter is a process in which the quanta or energy-units of the radiation are transferred from the field to the material body or *vice versa*. Unquestionably, therefore, the quantum theory is the proper basis for the interpretation of the facts of visual experience.

The faculty that our eyes possess of perceiving colour bring the phenomena of vision into the closest relationship with the basic notions of the quantum theory. Light which appears as a sharply-defined line in the spectrum is composed of energy-quanta which are all equal. The quantum of energy varies with the position of the spectral line, being the lowest when it is at the red end and largest when it is at the violet end of the spectrum. Thus, the magnitude of the energy quantum varies *pari passu* with the colour of the perceived light. Every one of the different colours we can perceive in the spectrum—and, of course, they are very numerous—has thus an equal claim with the rest to be considered as a primary colour and as a fundamental visual sensation.

Thus, the sensations excited by monochromatic light which is physically the simplest form of radiation play the basic role in physiological optics. These sensations are of two sorts, viz., the luminosity and the colour. When a continuous spectrum, as for instance that of a brightly illuminated cloud in daytime, is viewed through a pocket spectroscope, it is seen that the luminosity is a maximum somewhere in the greenish-yellow part of the spectrum and falls off to very low values as we approach either end of it. Figure 1 in the text represents the variation of the luminous efficiency of radiation over the entire spectrum as determined by various observers. The spectrum has for convenience been demarcated in the figure into six different sectors of colour, violet, blue, green,

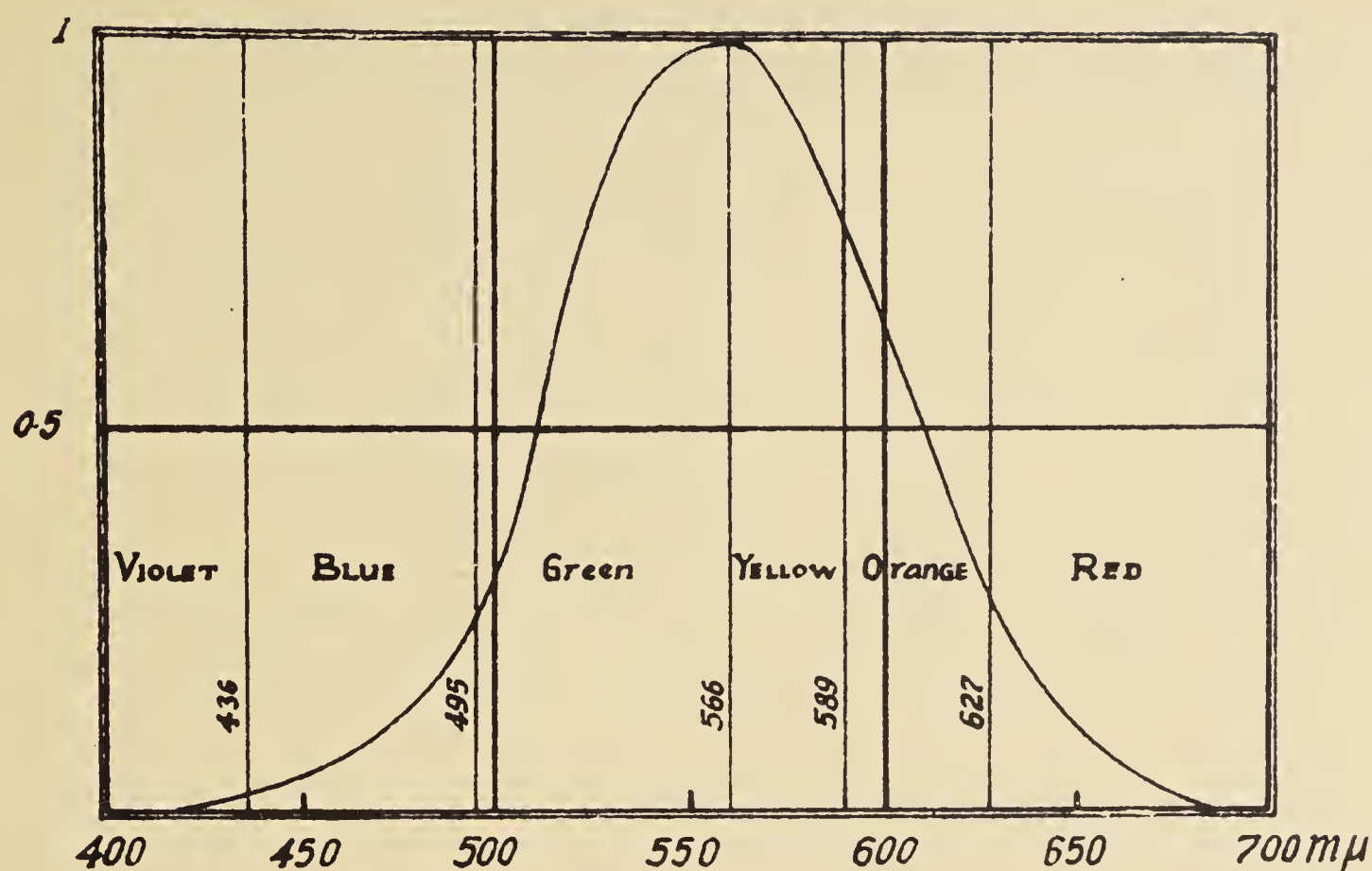


Figure 1. Colour and luminous efficiency in the spectrum.

yellow, orange and red, the wavelength limits between which have been taken as 436, 495, 566, 589 and 627 $m\mu$ respectively.

A highly significant feature of the visual perception of monochromatic light is the ability displayed to distinguish between the colours of closely adjacent regions in the spectrum. This is exhibited in figure 2 which shows the smallest change in wavelength that suffices in different parts of the spectrum to produce an observable change in colour. It will be seen from the diagram that a change of 3 $m\mu$ in wavelength suffices for the purpose over the greater part of the spectrum. The curve shows a series of dips at 436, 495 and 589 $m\mu$. These dips appear at the locations in the spectrum where the observed colour changes from violet to blue, from blue to green and yellow to orange respectively. The very high sensitivity displayed in the latter two regions is particularly remarkable.

In his address on "Light, Colour and Vision" to the XIX International Ophthalmological Congress held at New Delhi (Reference 1), the author summed up the results of his earlier investigations on the physiology of vision published in these *Proceedings* (References 2 and 3). Those investigations sought to discover the role of the retina in vision and the mechanism of its functioning in the perception of colour. The facts of observation embodied in figures 1 and 2 and the results of a detailed study of the visual process using a new and powerful method devised by the author formed the basis of the researches. We shall not go over the same ground here. The present memoir concerns itself with a different but highly important subject, viz., the colours of non-homogeneous light, in other words, with the visual sensations excited by polychromatic radiation.

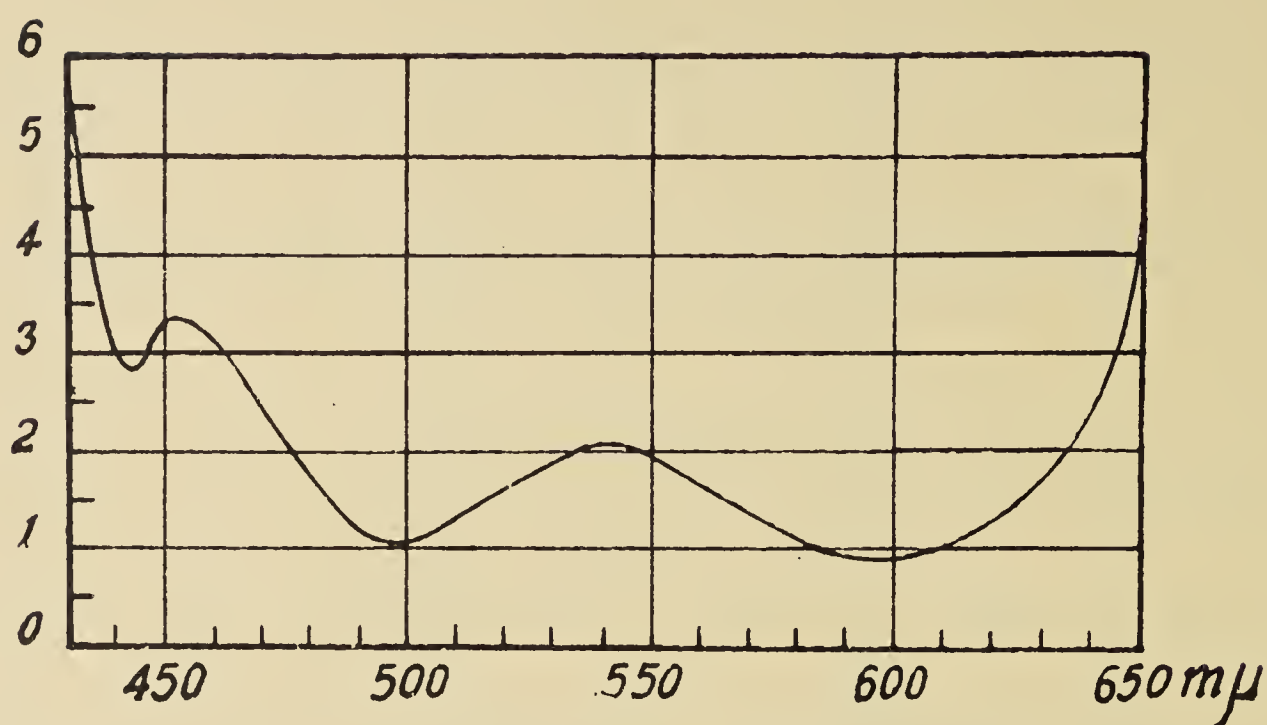


Figure 2. Colour discrimination in the spectrum.

A familiar example of the dependence of the colour of non-homogeneous light on its spectral composition is furnished by the thermal radiation from a heated body at various temperatures. The energy distribution in the continuous spectrum of such radiation alters with rise of temperature in such manner that the perceived colour passes through the well-known sequence ranging from a dark red at low to a brilliant white at high temperatures. This is a particularly simple case. In general, however, the spectral character of polychromatic radiation is capable of an unlimited range of variation. The energy density may vary from point to point in the spectrum and such variations may be of large magnitude. We have to consider the nature of the visual sensations excited by the light in all such cases.

The practical importance of giving an accurate description of the colour of commercial products has resulted in a great deal of attention being given in the past to the subjects of colour specification and colour measurement. We shall not here stop to discuss the methods adopted for such purposes and the ideas on which they are based. We shall also defer comment on the various conclusions of a general nature which have been arrived at from the earlier studies on colour. The approach to the subject in the present memoir is of an altogether different nature. It is based on the following considerations. *Firstly*, it is clear that in dealing with a subject of such complexity, it is necessary to base oneself on observational data of a comprehensive character obtained by methods which do not involve any particular assumptions regarding the visual mechanism and what it is or is not capable of achieving. For, only by such unbiassed observations that we can obtain a true picture of the reality. *Secondly*, it is evident that a vast mass of material suitable for investigations on colour and its perception is available to us in the products of plant life. The leaves, flowers and fruits of trees, shrubs and other forms of vegetation are indeed the most familiar objects manifesting colour

met with in the organic world. They are objects of profound interest to us from various other points of view, but, to the student of colour, they are invaluable. Being products of biological activity, they conform to set patterns and there is therefore no difficulty in repeating observations made with any particular type of material and comparing the results with those given by other materials. Further, a great range of colours is available for study and this is particularly so in the case of flowers where efforts of horticulturists have succeeded in producing a great many new varieties exhibiting fresh hues and patterns of colour.

In the course of the studies described in the memoir, several surprising observations were made regarding the spectral composition of the light which gives rise to the observed colour in various cases. These observations indicated the need for a fresh consideration of the mechanism of the perception of the colour of polychromatic radiation. In presenting the results, however, it appeared desirable to set out the actual facts of observation in detail. This has been done in the various individual parts into which the memoir is divided, each part dealing with a particular case or a set of cases with special features of their own. The concluding parts of the memoir bring together the results and discuss the problem of polychromatic colour perception in the light of the actual facts and the principles of the quantum theory.

Summary

Monochromatic light is composed of energy-quanta which are all equal. Our perception of colour is thereby brought into the closest relationship with the notions of the quantum theory. Polychromatic light, however, stands on a different footing and the problem of the colour which it exhibits demands separate consideration. The relationship between the spectral composition of such light and its observed hues can only be ascertained only by the observational study of a great number of cases. It is pointed out that a vast mass of material exhibiting colour and highly suitable for investigations of this nature presents itself to us in the products of the biological activity of trees and plants, viz., their leaves, flowers and fruits.

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Floral colours and the physiology of vision— Part II. The green colour of leaves

SIR C V RAMAN

(Memoir No. 137 of the Raman Research Institute, Bangalore-6)

Received June 4, 1963

Nearly all vegetation—from the blades of grass on the ground to the tops of lofty trees in the forest—has green as its characteristic and dominant colour. In this part of the memoir, we shall concern ourselves with the question, what is the origin of this colour? In other words, what is the spectral character of the radiation that excites this sensation in our visual organs? The answer to the query that emerges from the investigation is a surprising one. We shall in the course of our enquiry have much to say also about other questions, particularly the following. What is the relationship between the perceived colour and the absorption spectra of the pigments responsible for it? Why do different species of plants, shrubs and trees exhibit different shades of green in their foliage? What is the origin of the progressive change of colour following its first appearance of a leaf during its further development to full size and maturity?

A spectacular display of colour is that provided by a rice-field grown under irrigation, when after the seedlings have been transplanted, they multiply and cover the whole area. In bright sunshine, the field appears as a brilliant sheet of green, the exact shade of the colour depending on the state of growth. Viewing such a field through a direct-vision pocket spectroscope and comparing the spectrum then seen with that of the sunlit sky above the field, it is found that the violet and blue parts of the spectrum are absent in the light of the rice-field, while, on the other hand, the green and red sectors are both conspicuous and are of comparable strength. The superposition of the green and the red should have resulted in the field appearing of a golden-yellow colour instead of the bright green which it actually exhibits. Indeed, when sky-light is viewed through a glass filter of a golden-yellow hue, its spectrum also covers the green and red sectors and resembles that of the rice-field. Why then does the rice-field with a similar spectrum appear green instead of golden-yellow? The answer to this question emerges when the spectral composition of its colour is critically examined. We may usefully begin with a few remarks on the techniques of observation.

Even the thinnest of leaves when held up in sunlight does not permit of the sun's disk being seen through it. In other words, the incident light is completely diffused

or scattered besides suffering absorption within the material. It is very commonly the case that the upper and lower surfaces of a leaf present a very different appearance. The former exhibit in diffuse daylight a deeper colour and are also smoother. In consequence, when held at the proper angle to a beam of light incident on it, there is an observable reflection or glitter at the surface. On the other hand, the colour of the lower surface appears diluted by admixture with white light and by reason of its roughness, the regular reflection by the surface is weakened and may indeed not be noticeable at all.

In the circumstances stated above, we have two distinct and alternative methods of studying the colour of green leaves. The first is to observe the *upper* surface of the leaf holding it towards the light in such position and viewing it at such an angle that the surface reflection or glitter is unobservable and only the light emerging from the interior of the leaf is seen. The second method is to observe the light which emerges *through* the leaf when it is held up against the source of light. In the latter case, the slit of the observing spectroscope may be brought up close to the leaf. It then makes no difference which side of the leaf faces the source of light. In either case, it is desirable to use a powerful source of illumination. Indeed, direct sunlight is most suitable, though useful observations may also be made by holding up the leaf against the sky or alternatively using a powerful artificial source such as a tungsten-filament lamp of high candle power. Quite simple methods suffice for making the observations, a direct-vision pocket spectroscope being that all is needed. It should be provided with a wavelength scale capable of being focused independently and also capable of being adjusted laterally so that its readings can be checked against those of the lines in the solar spectrum.

The colour of leaves depends a good deal on the species under study. The colour also exhibits very significant changes during the progress of a leaf to maturity after its first appearance. Further significant changes appear when it has passed maturity and turns yellow before finally dropping off. These changes in colour, so far from being a source of embarrassment in the investigation, are actually helpful since they enable us to correlate the observed variations of colour with the changes in its spectral composition and thereby assist us in understanding the nature of the relationship between them.

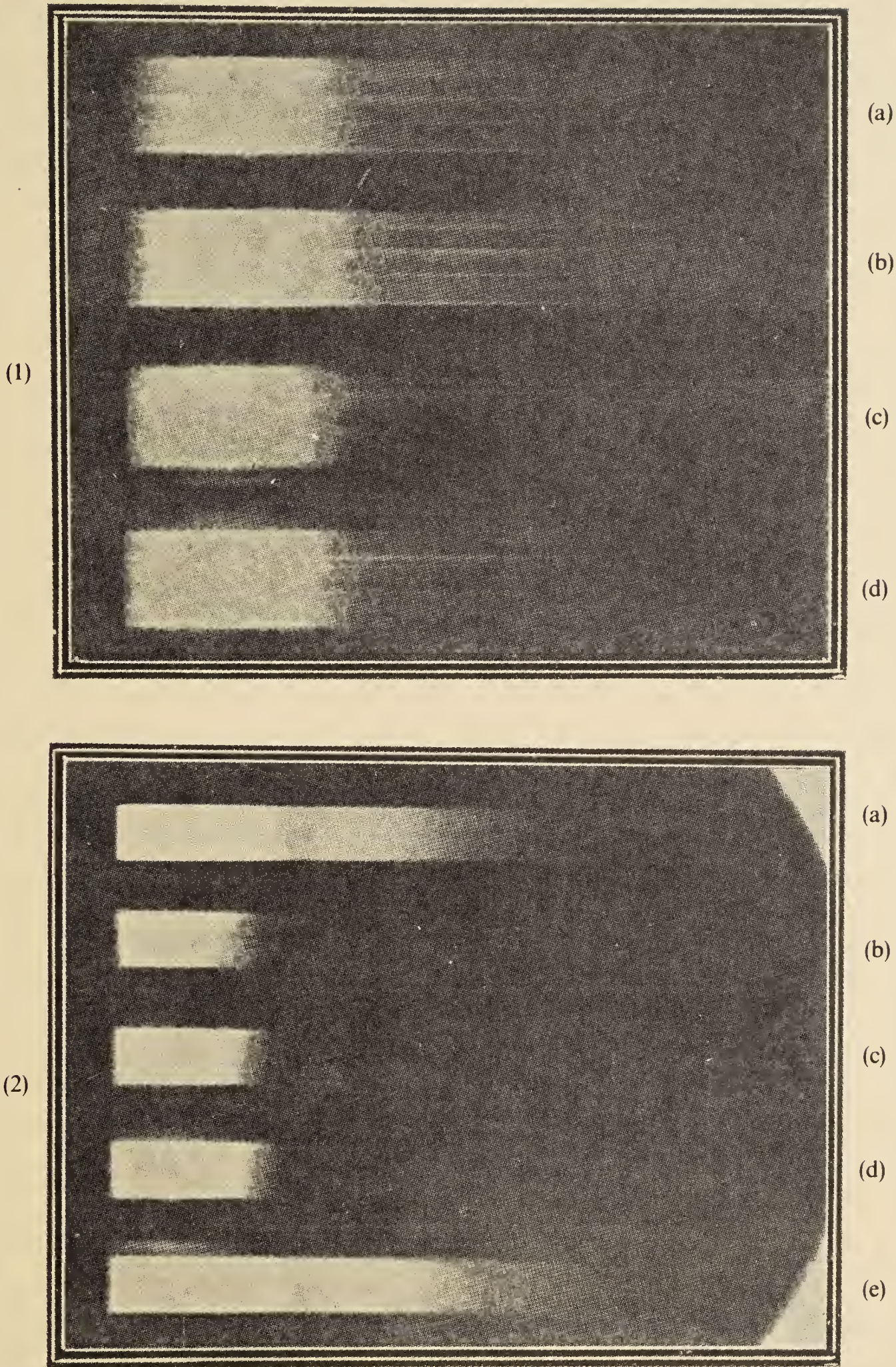
We may at this stage turn our attention to the colouring matters whose presence in green leaves has been proved by extraction with suitable solvents and their chemical identity established after their separation from each other by appropriate methods. These colouring matters have been found to be of two kinds, viz., the carotenoids and the chlorophylls respectively. The carotenoids present in green leaves are of two kinds, viz., β -carotene and dihydroxy- α -carotene or xanthophyll. The chlorophylls are also two in number and have been designated as chlorophyll (*a*) and chlorophyll (*b*) respectively. The absorption spectra of the carotenoids in a state of solution have been thoroughly investigated. β -carotene and xanthophyll exhibit somewhat similar absorption

spectra which appear predominantly in the wavelength region between 350 and 500 $m\mu$. At wavelengths greater than 520 $m\mu$ the absorption by these carotenoids is quite negligible. Chlorophyll (*a*) and chlorophyll (*b*) behave a little differently from each other. Chlorophyll (*a*) exhibits two pronounced maxima of absorption, one near the red end of the spectrum at about 660 $m\mu$ and the other in the violet at about 420 $m\mu$; between 640 and 450 $m\mu$, its absorption is very weak, but there is a perceptible increase in the wavelength range between 600 and 630 $m\mu$ with a distinct maximum at 615 $m\mu$. The principal absorption maxima of chlorophyll (*b*) appear respectively at 640 and 460 $m\mu$, while between 620 and 480 $m\mu$ its absorption by it is very weak, though a small rise appears around 590 $m\mu$.

It is necessary here to remark that the absorptive behaviour of the pigments as exhibited in the green leaves is not necessarily identical with that of the same materials separately in a state of solution. Nevertheless, the results quoted are useful as aids in the interpretation of the observations made with green leaves. Holding up a green leaf against a brightly lit sky and examining the light transmitted through it with a pocket spectroscope, it is found that the spectrum seen lies between the limits 520 and 645 $m\mu$. The position of these limits is not found to differ sensibly as between leaves showing a light green and a dark green colour respectively. Nor do these limits alter appreciably when we examine leaves in different stages of growth. Using bright sunlight, however, a feeble extension of the spectrum beyond 645 $m\mu$ to greater wavelengths can be observed. The dark absorption bands evidently due to chlorophyll lying in that region can then be seen. Likewise, using sunlight, the short wavelength limit is pushed down to about 500 $m\mu$.

The cut-off apparent at 500 $m\mu$ and complete at 520 $m\mu$ is clearly ascribable to the absorption by the carotenoid pigments. This is indicated by the fact that leaves which have turned yellow also exhibit a cut-off at 520 $m\mu$. Likewise, as we shall see later on, the petals of flowers with a golden-yellow hue ascribable to the presence of carotenoid pigments also exhibit a cut-off at the same wavelength. We thus arrive at the conclusion that the wavelength limits between which the light transmitted by green leaves has a sensible intensity, viz., 520 and 645 $m\mu$ are set respectively by the absorption due to the carotenoid pigments and the chlorophylls.

From the remarks and observation set forth above, it is clear that the green colour of leaves which we perceive is *not* a consequence of the powerful absorption by chlorophyll at the red end of the spectrum. Indeed, this region is of such low luminosity that its removal can have no sensible effect on the observed colour. *Actually, the operative factor is the absorption by the pigments present in the leaf of the yellow region of the spectrum.* This absorption is not strong. It nevertheless suffices profoundly to alter the character of the visual sensation excited by the light which has traversed the material containing these pigments. Indeed, on a careful examination of the spectrum of the light emerging through a green leaf, it is evident that the yellow sector in the wavelength range between 570



Figures 1 and 2. (a) and (b). Spectrum of green leaf. (c) and (d) Spectrum of yellow flower. 2 (a) and (e). Spectrum of light source. (b), (c) and (d). Spectrum of *Bignonia grassilis*.

Plate I

and $590\text{ m}\mu$ is weakened relatively to the regions on either side of it. Such weakening is appreciable even with the thinner and immature leaves and is conspicuous with the thicker and maturer leaves. The yellow sector is completely absent in the case of leaves which are dark green in colour. Thus, the differences in the observable colour of the leaves in these different cases are clearly ascribable to the variations in the extinction of the yellow part of the spectrum relatively to the green and to the orange and red sectors on either side of it.

As the yellow sector of the spectrum is a part of which the luminous efficiency is high, it is only to be expected that its extinction would have a readily observable effect on the perceived colour of the emerging light. Even so, it remains to be explained why the part of the spectrum in the wavelength range between 590 and $645\text{ m}\mu$ which is observable even with the thickest and darkest leaves and whose visual brightness is certainly not negligible in comparison with that of the spectral region between 520 and $570\text{ m}\mu$ seems to exercise little or no influence on the perceived colour. While it is undoubtedly the case that the red is weakened relatively to the green in the light which penetrates the leaf, the fact that it has no visual effect indicates that in the absence of the yellow sector which is the connecting link between the green and the red, the green sector masks the effect of the red, in other words, prevents its coming within the range of perception.

As visual observations of the spectral transmission by green leaves present no difficulty, any observer can satisfy himself regarding the statements made above. It appeared, however, desirable to exhibit the facts objectively with the aid of photographically recorded spectra. The non-uniform sensitivity of panchromatic films in the spectral region under consideration makes it rather difficult to accomplish this in a satisfactory manner. That the spectral ranges of transmission by a green leaf and by a yellow flower are not very different is, however, easy enough to exhibit in spectrograms. Figures 1 and 2 reproduced in plate I are intended to do this. Figure 1 exhibits the recorded spectra of a green leaf and of a yellow flower side by side and figure 2 those of the yellow flower alone. The red end of the spectrum appears at the extreme left in each case.

Postscript dated the 9th August 1963: Since the foregoing paragraph was written, it has been found possible using an "Agfa Raman Plate" to obtain satisfactory spectrograms demonstrating the effects described above.

Summary

The light emerging with sensible intensity after passage through the material of a green leaf is observable in the spectral regions of green and red extending from 520 to $645\text{ m}\mu$. These limits are set by the carotenoid and the chlorophyll pigments in the leaf which exercises powerful absorption at smaller and at greater wavelengths respectively. The characteristic absorption bands of the chlorophylls can be seen under strong illumination at the extreme red end of the

spectrum. But they do not sensibly influence the observed colour of the leaf, since the extreme red is of very low luminous efficiency. Actually, the operative cause which determines the observed colour of the leaf is the absorption by the leaf pigments manifested in the yellow region of the spectrum between 570 and 590 m μ . The colour of the leaf appears a deeper green with increasing strength of that absorption.

Floral colours and the physiology of vision— Part III. The spectrum of the morning glory

SIR C V RAMAN

(Memoir No. 137 of the Raman Research Institute, Bangalore-6)

Received June 4, 1963

As has been remarked in the first part of this memoir, a vast mass of material suitable for investigations on the perception of colour is available to us in the products of the plant world. The reason for the choice of the “Morning Glory” as the first of the flowers to receive attention in this memoir is the remarkable nature of the chromatic effects which it exhibits. These are of a challenging nature and present features of fundamental interest.

The botanical name of this climbing and twining creeper is *Ipomea learii*, and it is to be found in many Indian gardens. When trained to cover a screen, it presents a magnificent sight in the early mornings, its green foliage appearing studded over with numerous trumpet-shaped flowers (see figure 1, front view and figure 2, side view in which the flower appears with half its natural size). The five divisions of the trumpet-shaped expansion are very thin and are held together by five ribs of a

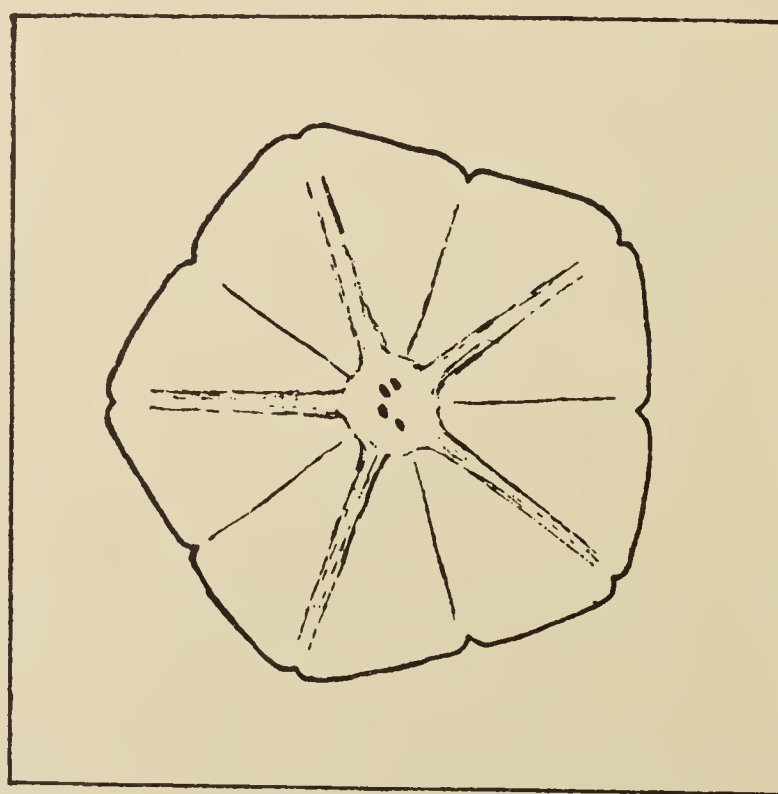


Figure 1. Morning glory (front view).

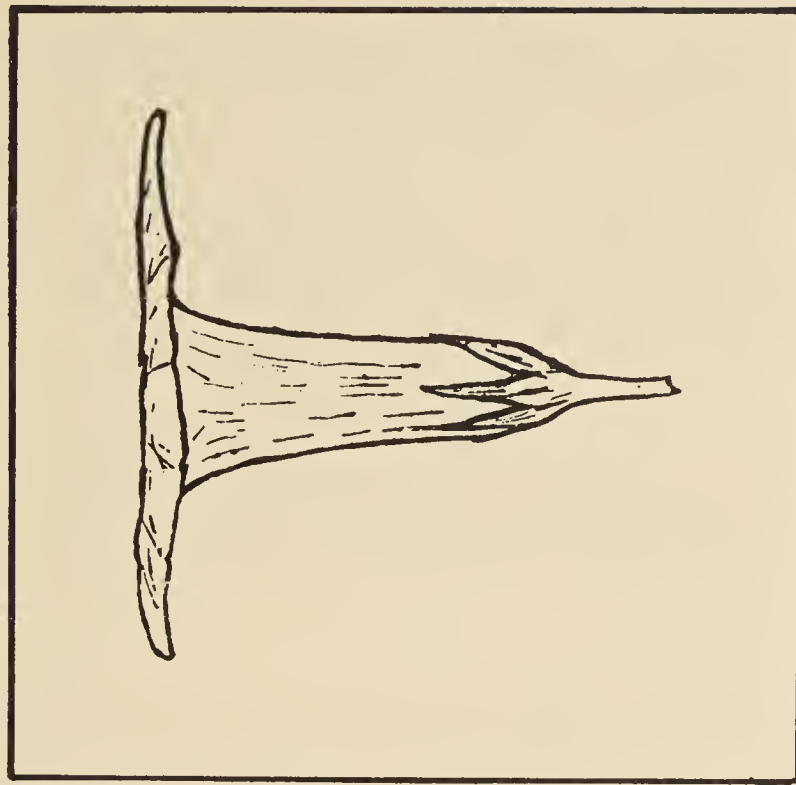
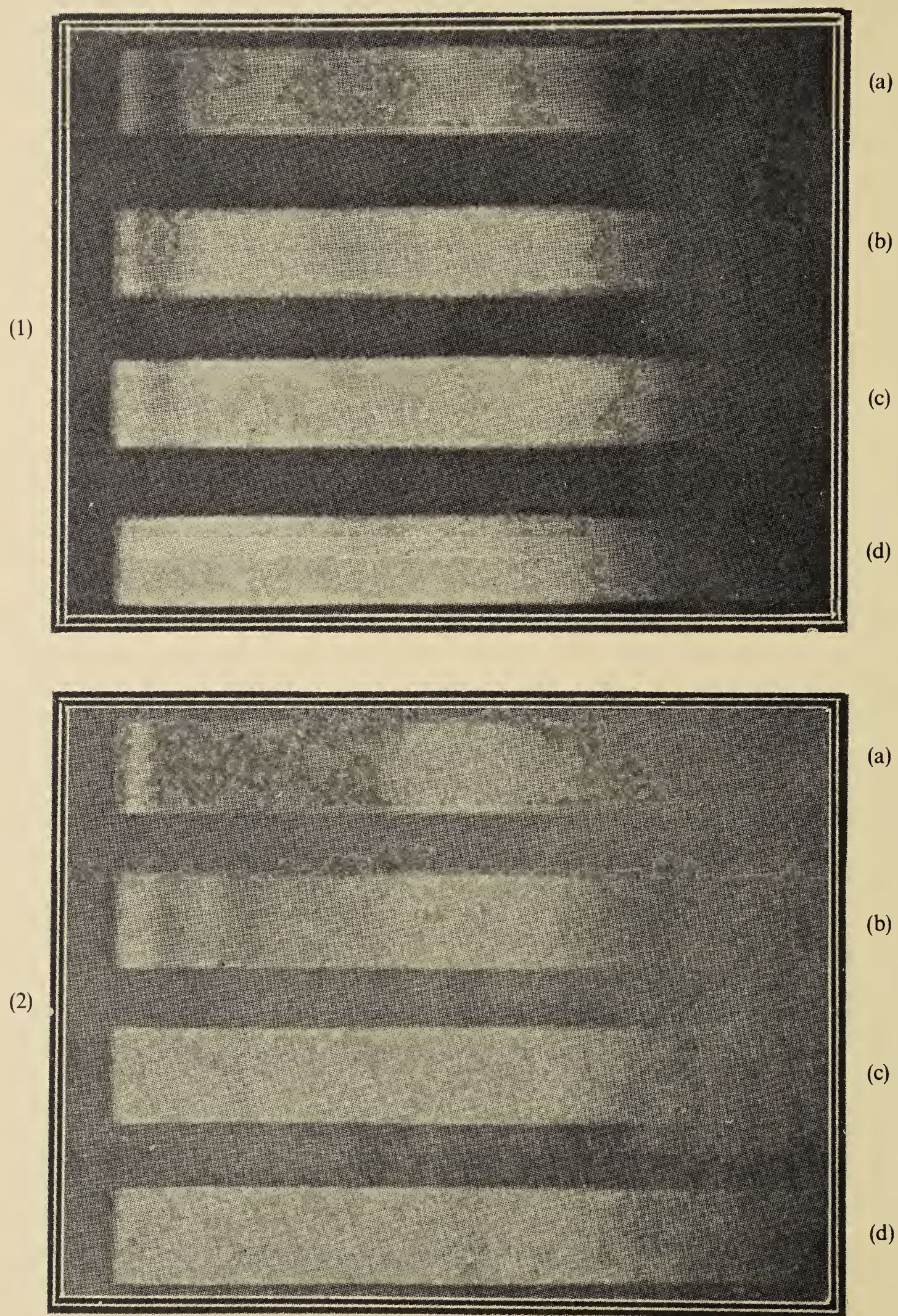


Figure 2. Morning glory (side view).

purplish tint, while the intervening membranes exhibit a brilliant blue colour of almost spectral purity. The colour is best seen when the flower is viewed from the front and is then a deeper blue than that seen by the light which has traversed the membranes. The reason for the difference is obvious. When the flower is viewed from the front, in other words, by the light that is thrown back towards the source of light, the thickness of the absorbing layer is effectively doubled. Though the membranes exhibiting the colour are thin, they do not allow the sun to be seen through them when the flower is held between the light and the eye. In other words, they function as diffusing media for all wavelengths in the spectrum.

A surprising fact emerges when a spectroscope is used to examine the composition of the light perceived by the eye as being of a brilliant blue colour. The spectroscope may be directed towards the flower, either from the front or from the rear. In the former case, the light examined is that diffused backwards, while in the latter case the light examined is that diffused forwards. The effect observed is very similar but differs in detail in the two cases, by reason of the effective thickness of absorbing material being greater in the light diffused backwards. In either case, the spectrum exhibits a strong absorption in the region of the spectrum extending from 590 to 635 $m\mu$. The absorption terminates sharply at the latter wavelength, while in the region between 570 and 590 $m\mu$, it is also observable but less strongly. The rest of the spectrum between the extreme violet and the extreme red exhibits no other absorption or change of relative intensities. As observed through the spectroscope, the red of the spectrum appears the most intense, the green follows next in order, while the violet and blue sectors appear as visually the weakest.

We may now ask, why does the flower exhibit a brilliant blue colour to the eye?



Figures 1 and 2. 1. Spectrum of the morning glory and comparison spectrum. 2. Spectrum of the blue lily and comparison spectrum.

Plate I.

The red and the green sectors are present in their full strength relatively to the blue sector and indeed they appear in the spectroscope as much brighter than the blue. Nevertheless it is the latter that is perceived by our eyes and not the former. The situation may be stated as follows: The complete spectrum extending from the extreme violet to the extreme red presents to our visual perception the sensation of white light. When we remove from the spectrum the strip of wavelengths between 570 and 635 $m\mu$, in other words, we cut out the yellow and orange sectors, the visual effect is transformed to a bright blue of almost spectral purity. The only reasonable explanation appears to be that in the particular circumstances of the case, the red and green in the radiation are masked or screened off from perception by the blue part.

It appeared desirable to confirm the visual observations described above by objective methods. For this purpose, the spectrum of the light transmitted through the flower was recorded photographically using a Higler constant deviation spectrograph on an Agfa panchromatic film. A tungsten filament lamp was used as the source of light in conjunction with a filter of copper sulphate solution so as to reproduce daylight conditions as nearly as practicable. To enable the effects of the varying sensitivity of the photographic film over different parts of the spectrum to be recognised and taken account of, a spectrogram of the light-source alone was recorded with a suitable exposure on the same film and the spectrogram of the flower was recorded with three different exposures so as to admit of a proper comparison with it. Figure 1(a), (b), (c) and (d) in plate I reproduce the spectra thus recorded. Figure 1(d) is that of the source of light alone, while figures 1(a), (b) and (c) are the spectra of the flower recorded with three different exposures. In each case, the red end of the spectrum appears on the left while the violet end appears on the right.

In figure 1(d) in plate I, the region in the middle of the spectrum of low photographic sensitivity is recognisable. This also appears prominently in the three other spectra (a), (b) and (c). It should, therefore, be excluded from consideration. The strong absorption by the flower in the orange sector is recorded as a dark band in the spectra. It is also evident on comparing them with figure 1(d) in the plate that the material of the flower does not exercise any sensible absorption elsewhere in the spectrum.

Summary

The flowers of the Morning Glory (*Ipomea learii*) exhibit a bright blue colour of almost spectral purity in daylight. Visual observations, confirmed by spectrum photographs, show that this visual sensation results from the removal of the yellow and orange radiations from the complete spectrum, the relative intensities of the red, green and blue-violet regions remaining unaltered. The effect observed may be interpreted as the result of the masking of the visual effect of the red and green sectors by the blue sector in the spectrum in these circumstances.

Floral colours and the physiology of vision— Part IV. The queen of flowers

SIR C V RAMAN

(Memoir No. 137 of the Raman Research Institute, Bangalore-6)

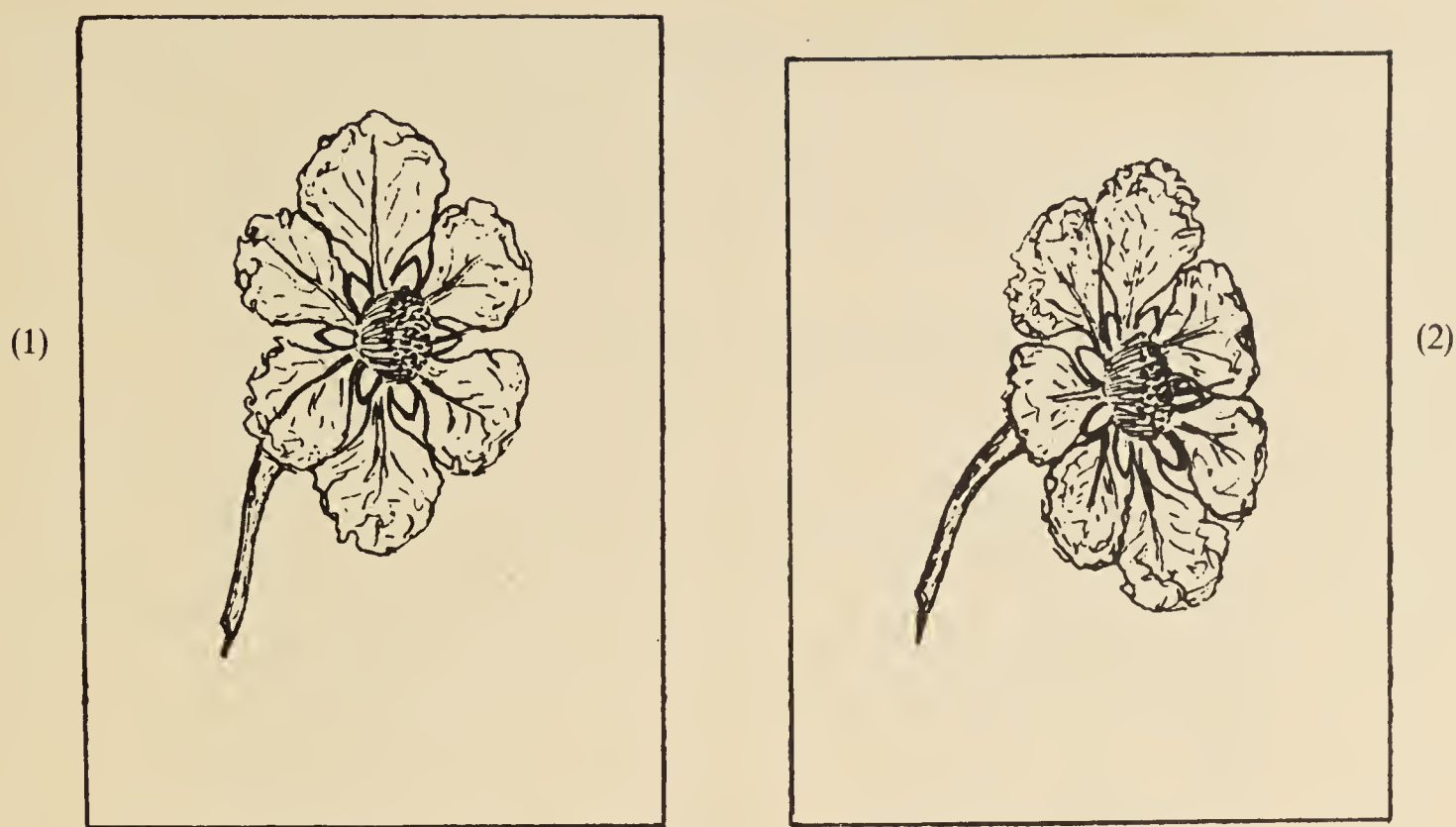
Received June 4, 1963

The forest tree named by the botanist Retzius as *Lagerstroemia Flos Reginae* bears great masses of magnificent flowers in the months of April to July each year and then presents an extremely handsome appearance. For that reason, the tree is sometimes referred to as the Pride of India. It grows to great sizes in appropriate soils and climatic conditions and is valued for the timber of high quality (known locally as Jarul) which it yields. By reason of its beauty when in flower, the tree has been extensively planted as avenues in cities and towns and also in gardens as an ornament. The flowers of *L. Flos Reginae* have been selected for special attention in this part of the memoir for reasons similar to those mentioned in the case of the “Morning Glory”.

In the coloured plate illustrating the flowers of *L. Flos Reginae* in the volume entitled *Some Beautiful Indian Trees* published by the Bombay Natural History Society, they are shown as six-petalled and of a bright pink colour. On the other hand, in the plate illustrating D V Cowen’s book on *Flowering Trees and Shrubs in India* published by Thacker and Co. of Bombay, they are also shown as six-petalled but of a beautiful purple colour. Actually, there are two distinct species or varieties of the tree, one bearing purple flowers and the other bearing pink flowers. In the gardens of this Institute, trees of both varieties were planted some years ago and their flowers have therefore been available for comparative study. It should be mentioned that occasionally there are seven instead of six petals, as has been mentioned in the works referred to earlier.

The flower-petals are very thin and are crinkled. This is represented in figures 1 and 2 which show the six-petalled and seven-petalled forms respectively reduced to half the natural sizes. Despite the thinness of the flower petals, they do not allow sunlight to penetrate directly through them, but only diffuse it. The spectral composition of the diffused light may be studied either in the forward or in the backward direction, with very similar results. Needless to say, the effects observed with the purple and with the pink flowers are entirely different.

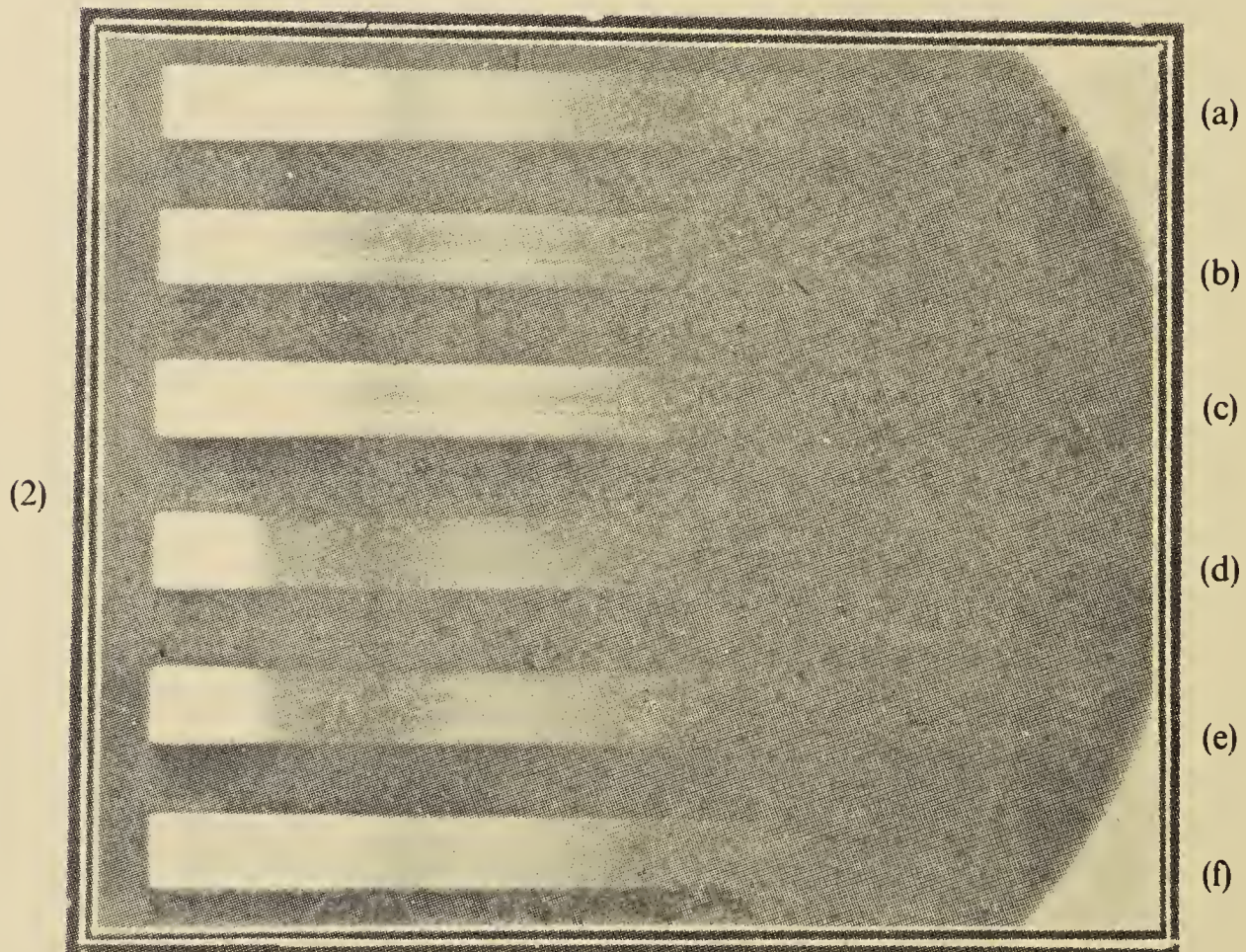
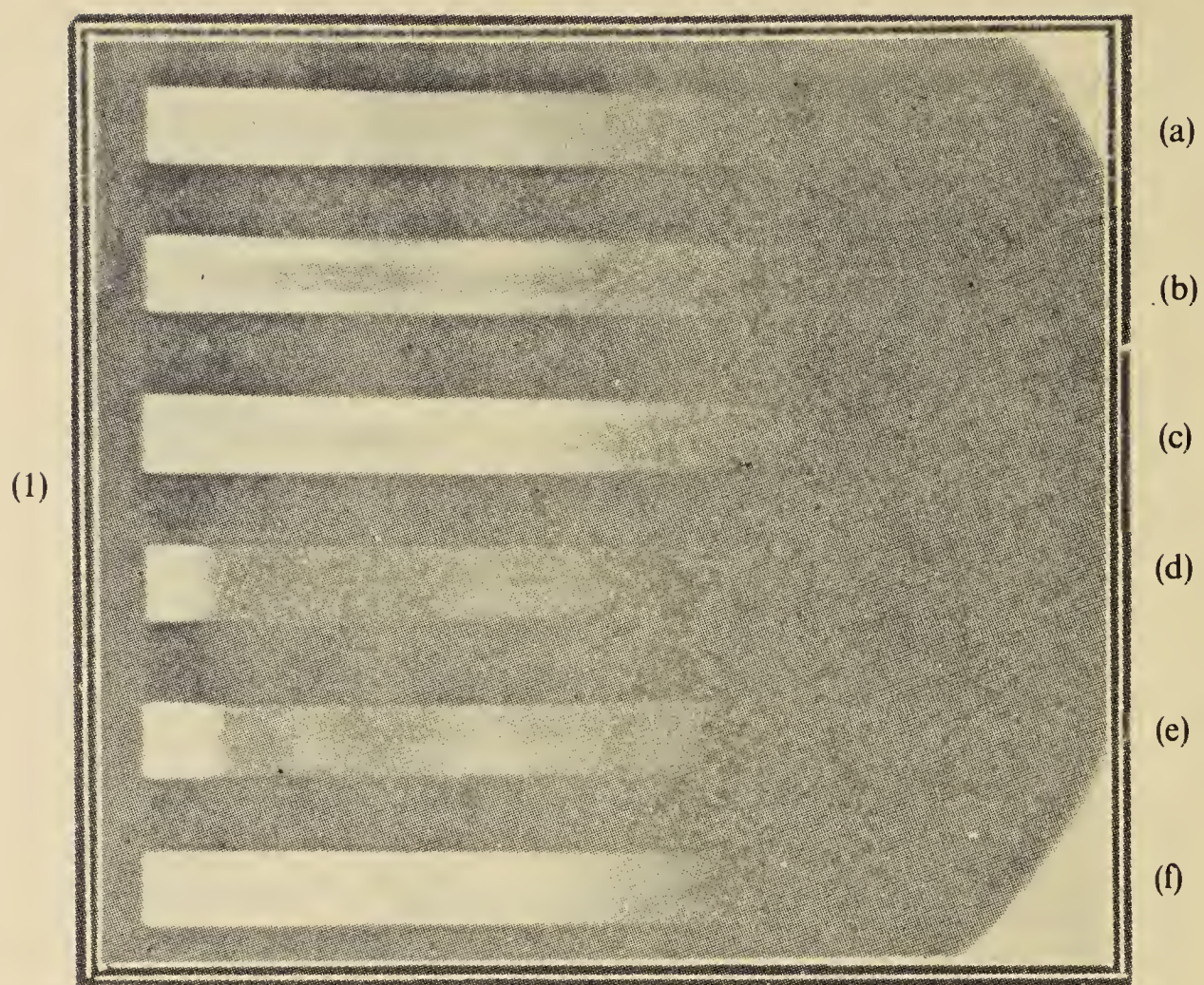
Strangely enough, the flower exhibiting a purple colours shows no absorption in the red, green and blue-violet sectors of the spectrum and these regions are seen



Figures 1 and 2. Flowers of *Lagerstroemia Flos Reginae*.

with their normally observed relative intensities. There is, however, an observable absorption of the yellow sector covering the region of wavelengths between 570 and 590 $m\mu$. The pink flowers behave differently. The red and the blue-violet regions appear in the spectrum with their normally observed relative intensities, but the green sector, ranging from 520 to 570 $m\mu$, appears greatly weakened. The absorption in the yellow by the purple flower and the absorption in the green by the pink flower are not very strong and hence it is not easy to exhibit them satisfactorily in a spectrum recorded by photography. But by putting two petals of each flower together and thus doubling the absorption path, it becomes easier to obtain satisfactory spectrograms.

Figures 1(a) and (f) in plate I are spectrograms of the light-source employed, while figures 1(b) and (c) are the spectrograms obtained with a single petal of the purple variety placed before the slit of the spectrograph, but with two different exposures. Figures 1(d) and (e) are spectrograms obtained likewise with two petals of the purple flower put together. The absorption band in the yellow sector of the spectrum can be clearly recognised in both of these figures (the diffuse band in the middle of the spectrum arises from the low photographic sensitivity in that region and should therefore be ignored). Figure 2(a), (b), (c), (d), (e) and (f) are spectrographic records obtained in a similar fashion with the pink flowers; (a) and (f) are spectrograms of the light-source, while (b) and (c) are the spectra recorded with a single petal of the pink flower placed in front of the slit of the spectrograph; (d) and (e) were recorded with two petals of the pink flowers held together. It can be seen on comparing the two sets of spectrograms that the absorption which gives rise to the purple colour in one case, and that which gives



Figures 1 and 2. 1. Spectra of the purple Lagerstroemia with comparison spectra. 2. Spectra of the pink Lagerstroemia with comparison spectra.

Plate I.

rise to the pink colour in the other case appear in quite different regions of the spectrum, as stated above.

Thus, in both cases, the chromatic behaviour of the "Queen of Flowers" presents us with what would seem strange anomalies to those who have adopted the current beliefs regarding the sensations excited by polychromatic light. Purple is the name given by them to the colour sensation excited by the superposition of red and violet, while green is the part of the spectrum which when superposed on purple should result in white light. Actually, as we have seen, the sensation of purple is excited by the entire spectrum of white light from which the yellow strip ranging from 570 to 590 $m\mu$ has been removed. Then again, the weakening of the green sector from 520 to 570 $m\mu$ in the spectrum leaving the rest unaltered should have resulted in a purple sensation. The actual result, as we have seen, is a bright pink.

Summary

The flowering tree *Lagerstroemia Flos Reginae* (also known as *L. Speciosa*) has two varieties bearing purple and pink flowers respectively. Spectroscopic examination shows that the purple colouration represents the entire spectrum of white light in which the limited region from 570 to 590 $m\mu$ is absent. The pink colour results from a weakening of the spectrum in the range of wavelengths from 520 to 570 $m\mu$.

Floral colours and the physiology of vision— Part V. The blue of the Jacaranda

SIR C V RAMAN

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The tree whose full botanical name is *Jacaranda mimosifolia* was originally a native of Brazil, but has been introduced into many tropical and sub-tropical countries. It is now a common sight in Indian gardens and is also a favourite avenue tree in towns and cities. Its foliage is as finely cut as a fern, symmetrical and elegant. But the beauty of the foliage is far excelled by the splendour of the flowers which the tree bears in profusion during the months of March to May in each year. Each fresh green stem growing from the old wood terminates in a large loose cluster of violet-blue flowers in great number, forming a spray of colour. An avenue of such trees is an unforgettable sight when from end to end every tree is swathed in blue. Illustrations showing the foliage, flowers and buds of the Jacaranda appear in the two books quoted in the preceding part of the memoir.

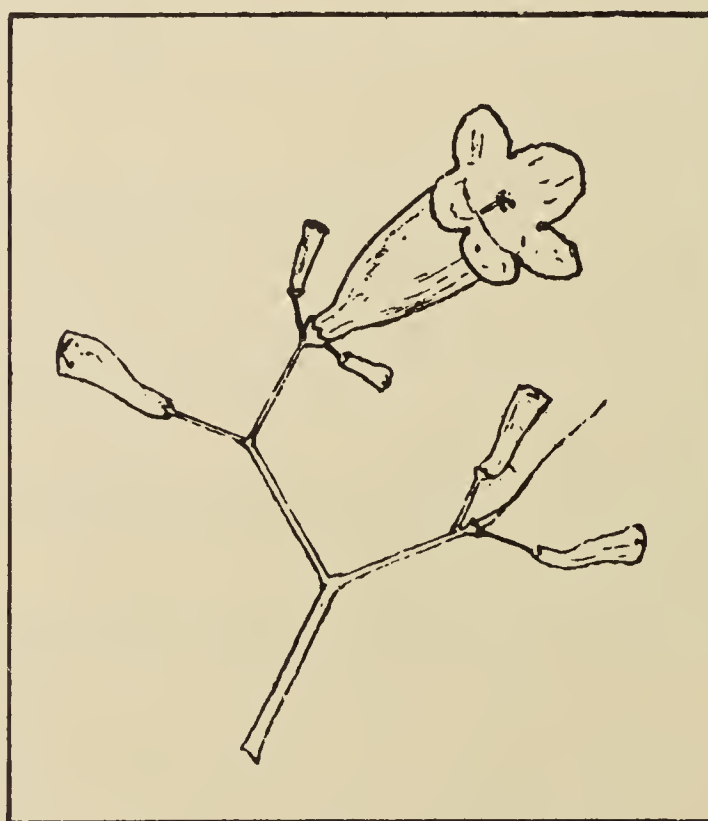


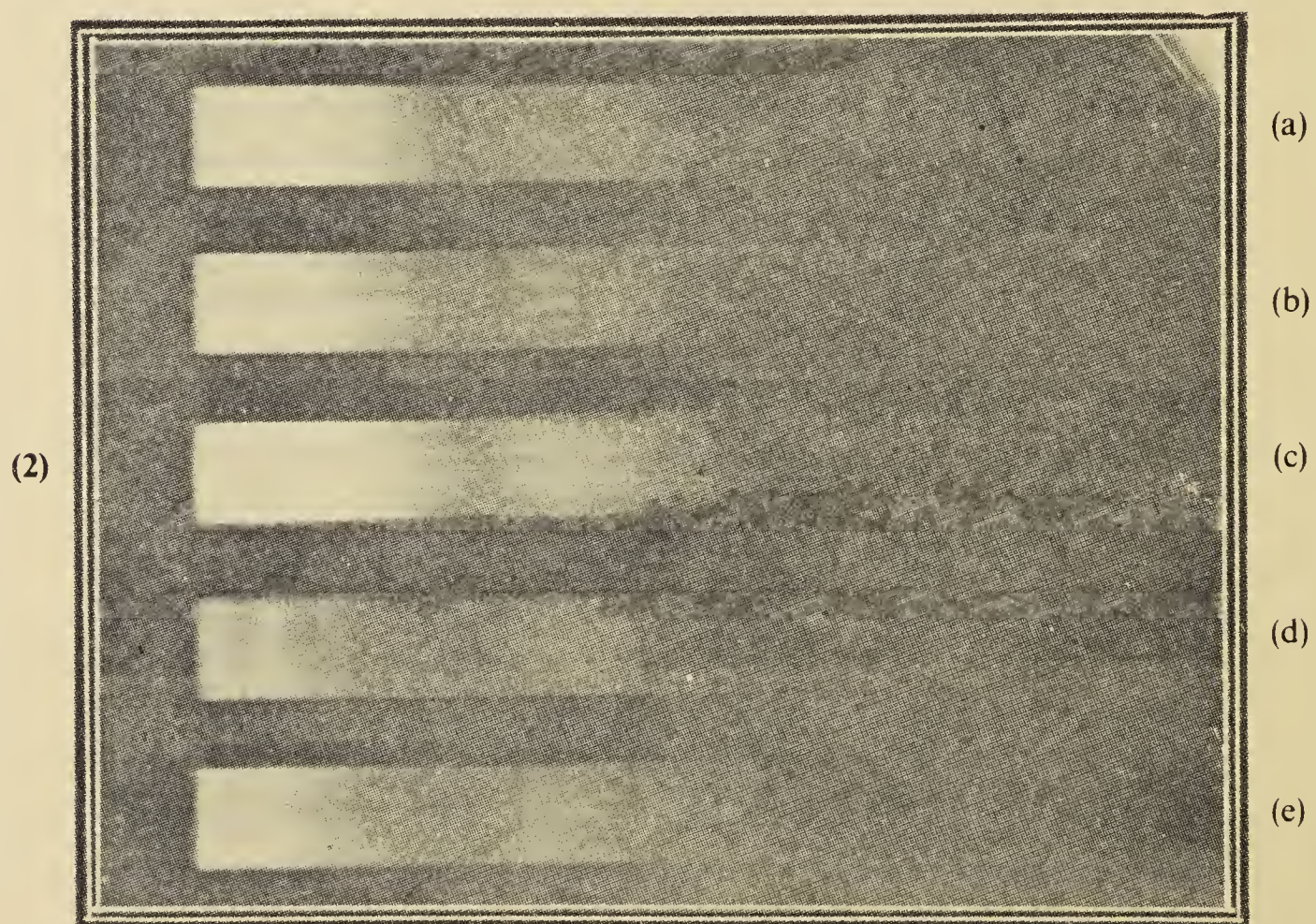
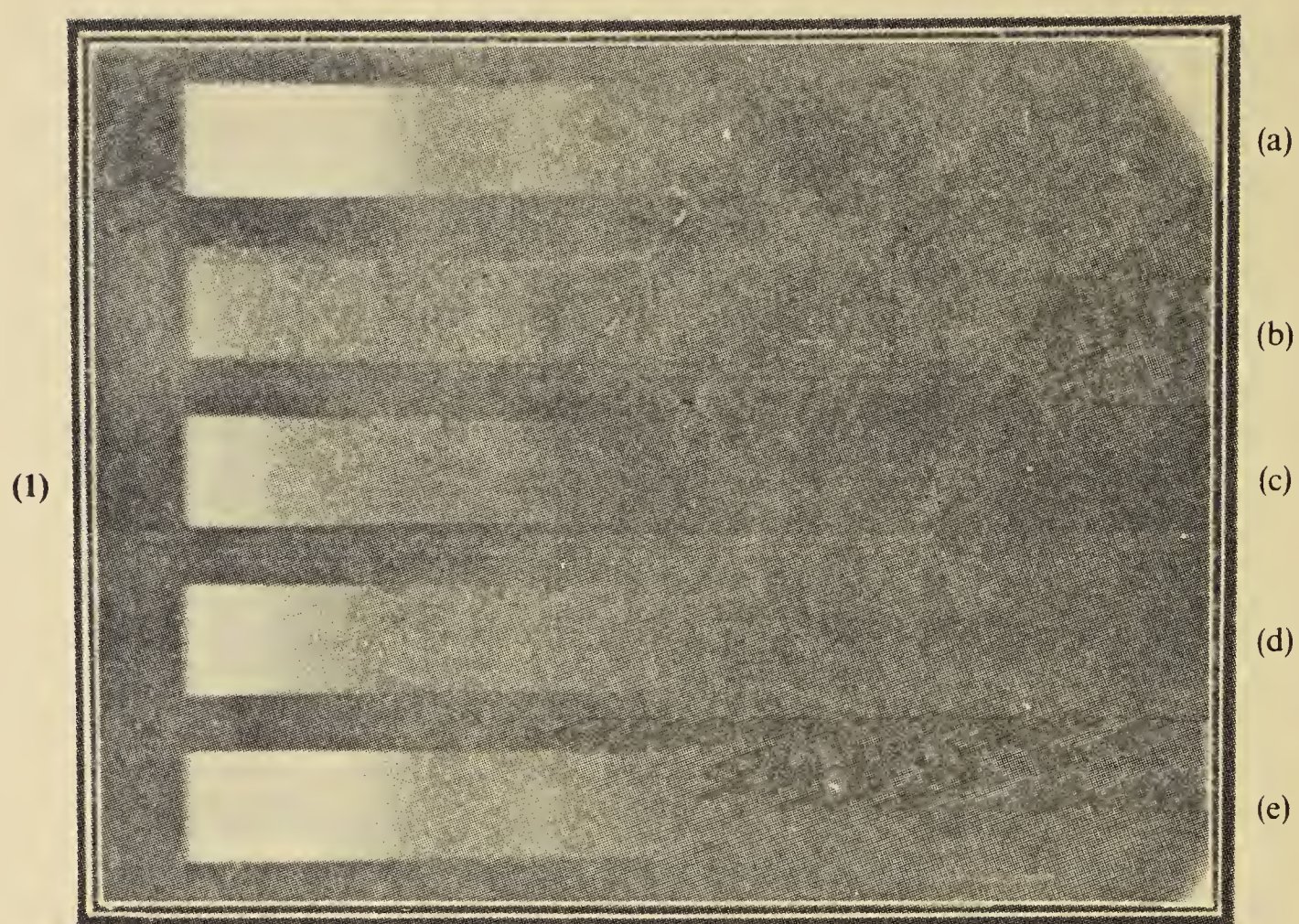
Figure 1. Flower and buds of Jacaranda.

Figure 1 in the text is a sketch of a single flower and a few unopened buds attached to it.

The unique character of the floral display of the Jacaranda invests the origin of the blue colour of its buds and flowers with much interest. Each flower is a bent swelling tube, about 5 cm long, which divides into five unequal lobes, two upcurving and smudged with white and the other three large and straight. As a result of this tubular shape, the colour exhibited by the flower arises in two different ways, firstly from the light which is diffused backwards by the outer surfaces of the tube and secondly from the light which was passed through the tube, suffering absorption and diffusion twice in its path. Both processes result in making the colour appear deeper than it would be after passage through a single layer of the absorbing material. It is worthy of note that the buds of the Jacaranda exhibit a deeper colour than the flowers. This may be ascribed to the concentration of the absorbing material in a smaller space. Even after dropping from the tree, the colour of the flower does not fade away. On the other hand, the colour deepens as the material dries up.

Examination of the spectral composition of the colour arising in either of the two ways stated above shows that the origin of the colour to be, firstly, a weak absorption in the yellow region of the spectrum in the wavelength range 570 to 590 $m\mu$, and another weak absorption in the spectral region between 630 and 640 $m\mu$. As the result of these two effects, the orange sector in the region of wavelengths between 600 and 620 $m\mu$ stands out as a bright band with darker regions on either side of it. The rest of the spectrum including the violet, blue and green sectors has its normal appearance without any change in relative intensities which could be visually detected. Thus, the blue colour of the Jacaranda flowers is ascribable to a weakening of two rather narrow sectors in the spectrum, viz., the region of the yellow and a region midway between the orange and the red.

The weakness of the absorptions and the non-uniformity of the photographic sensitivity of the panchromatic films make it rather difficult to portray them satisfactorily in a spectrogram. Better results are, however, obtained using material detached from an unopened bud, which as stated earlier exhibits the colour more vividly than the flower. Figures 1(a), (b), (c), (d) and (e) in plate I reproduce the spectrograms thus obtained; figure 1(a) and (e) are comparison spectra of the light-source employed, while (b), (c) and (d) reproduce the spectrograms recorded with the absorbing material covering the slit of the spectrograph and with three different exposures. The red end of the spectrum in each case is on the extreme left, while the violet is on the extreme right. The features mentioned above can be recognised in the reproduced spectra when they are compared with those of the light-source appearing as the first and the last of the series of five spectrograms.



Figures 1 and 2. 1. Spectra of blue Jacaranda with comparison spectra. 2. Spectra of the "Heavenly Blue" with comparison spectra.

Summary

Spectroscopic observations show that the blue colour of the flowers of the Jacaranda tree is ascribable entirely to two weak absorption bands, one appearing in the yellow and the other midway between the orange and red sectors, the rest of the spectrum of white light showing no other observable variation from its normal distribution of intensity.

Floral colours and the physiology of vision— Part VI. Comparative study of three cases

SIR C V RAMAN

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In this part of this memoir, we shall consider three cases, each of which by itself exhibits very interesting features. But when these features are compared with each other, highly significant facts emerge.

The tree known botanically as *Solanum grandiflorum* and popularly as the large-flowered nightshade or potato tree grows under favourable conditions to a height of 30 to 40 feet and flowers all the year round. The full-grown tree presents an astonishing sight with its large leaves and the immense number of bunches of flowers appearing on all its branches, each bunch itself holding a great many flowers. The shape of the flower is shown in figure 1, which also exhibits the stalk

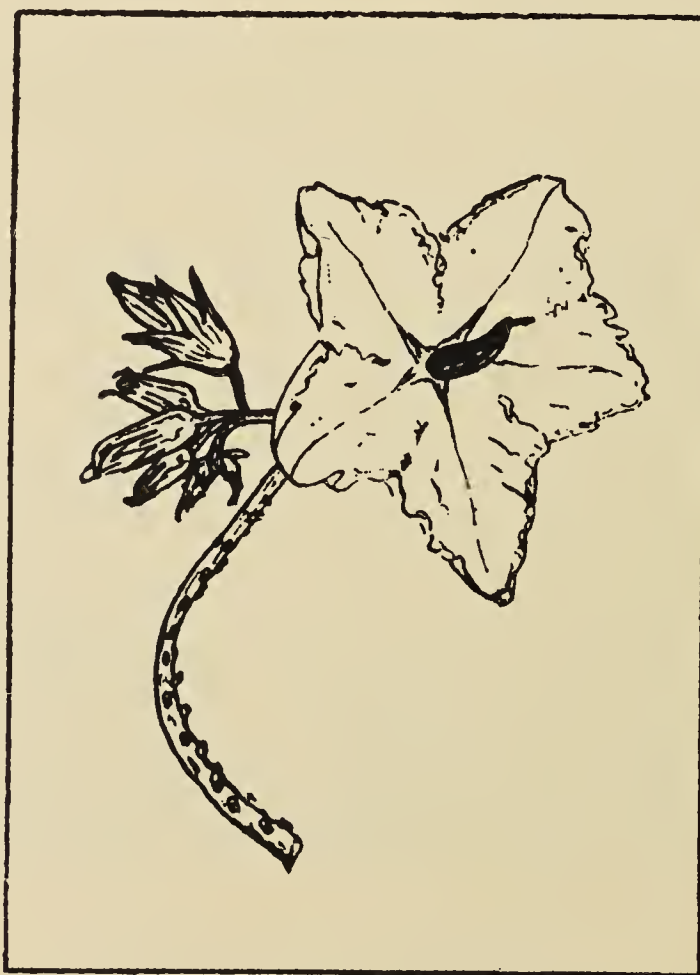


Figure 1. Flower, buds and stalk of *Solanum grandiflorum*.

carrying the flower and several other buds due to open in due course. The corolla has five lobes which are sharply pointed, while the anthers are large and yellow in colour. The illustration which appears facing page 135 of the volume entitled *Some Beautiful Indian Trees* published by the Bombay Natural History Society exhibits a characteristic feature of the flowering of the tree, viz., that the corolla of the flower which has opened out last in each branch exhibits a colour which in its hue and its saturation resembles a spectral violet; but the flowers which have appeared earlier show a progressive fading away of colour, and finally, they appear as a pure white traversed by a few streaks which are but a faint shadow of the original intense colouring. The ribs joining the centre of the corolla to the pointed tips of the lobes are coloured a little differently from the membranes which they hold together. These membranes are thin and presents a crinkled appearance. The corolla appears of a deeper and darker colour when viewed by reflected light than when viewed with the flower held between the observer's eye and the source of light.

The floating leaves and the flowers of a water-lily (*Nymphaea caerulea*) on their long stalks in a large cistern of water make a most colourful exhibit in the sunken garden attached to the author's residence at his Institute in Bangalore. Each flower has four sepals and numerous petals within arranged in regular order. The inner face of the sepals is of a purple colour, while the petals are definitely blue but with an unmistakable purplish tinge. The central part of the flower (sketched in figure 2) is of a brilliant golden-yellow hue, but the tips of the stamens are tinged with purple. The structure of the flower is exquisitely lovely, and its charm is enhanced by the colours and the attractive perfume which it exhales.

The luxuriant climbing plant, known to the botanist as *Thunbergia grandiflora* and popularly as "The Heavenly Blue" is to be found in gardens all over India. It



Figure 2. The blue water-lily.

can easily be recognised by its dense green curtain of foliage and the large blue flowers. Each flower consists of a longish stem, a thick green calyx and a long broad corolla. The calyx is contracted towards the base, pointed at the apex and nearly divides into two segments when the corolla emerges. This corolla is from two to three inches long. The tube is whitish outside, more yellow within and contracts upwards in the middle before dilating into a bell-shape which opens into five round spreading lobes. The base of each lobe, particularly the lower protruding one, exhibits streaks of a violet hue. The rest is of a lovely blue colour which rather resembles that of the Jacaranda flowers (figure 3 in the text).

We shall first consider the spectral composition of the light responsible for the "Heavenly Blue" of *Thunbergia*. This colour, though vivid, is far from being saturated. Actually, it is more violet than blue, especially in the case of the freshly opened flowers. The spectrum may be studied either by transmission or with the light diffused backwards towards the source. Similar features are observed in either case except that they are accentuated when seen by reflected light, owing to the absorption path being then effectively doubled. The spectroscopic observations show that the colour exhibited to our visual perceptions owes its origin principally to an absorption band in the yellow region of the spectrum between 570 and 590 $m\mu$. A distinct absorption is also noticeable around 630 $m\mu$, with the result that the orange of the spectrum between 590 and 620 $m\mu$ stands out as a bright band with darker regions on either side. A slight dimming of intensity in the spectrum around 540 $m\mu$ in the green sector is also detectable. It may be remarked that these features closely resemble those noticed with the flowers of the Jacaranda and discussed in the fifth part of this memoir. The similarity in hue is therefore not surprising.

The absorptions which give rise to the perceived colour of the *Thunbergia* flowers are by no means easy to exhibit in spectrograms, partly because they are rather weak and also because of the non-uniform sensitivity of the panchromatic films. The results may, however, be improved by recording the transmission through two petals held together. Of the five spectrograms reproduced as figure 2 in plate I of part V, figure 2(a) is of the light-source put in as a comparison; figure 2(b) and (c) are the spectra recorded by transmission through a single petal with two different exposures, while figure 2(d) and (e) were recorded with two petals held together.

The spectrum of the blue water-lily is of a different character. Its perceived colour owes its origin to an absorption in the orange region of the spectrum between 590 and 610 $m\mu$, and another in the green sector between 550 and 570 $m\mu$. These absorptions are weak and it is, therefore, not surprising that the perceived colour of the flower is not of a saturated hue. Hence, both for visual observations and for spectrum photography, it is useful to hold two petals together and to accentuate thereby the strength of the absorption. Figure 2(a), (b) and (c) in plate I of part III are spectrum photographs obtained in this manner, while (d) in the same plate is a spectrum of the light source put in for comparison.



Figure 3. Flower of *Thunbergia grandiflora*.

We shall now consider the most interesting of the three cases, viz., the flowers of *Solanum grandiflorum*. The intensity of colour exhibited by this flower is most remarkable. Indeed, it is even more striking than the colour displayed by the "Morning Glory" described in the third part of this memoir. In the present case, however, the colour is violet instead of blue. The best way of observing the colour and examining its spectral composition is to view the flower in sunlight with the observer having the sun behind him. What is then seen through the spectroscope appears almost incredible. The entire spectrum from the extreme violet to the extreme red is seen and is scarcely distinguishable from the normal spectrum of sunlight except that the yellow sector is absent. A sharp absorption edge appears at $600\text{ m}\mu$; on the longer wavelength side of this edge, the orange sector appears with its full normal intensity, while towards shorter wavelengths, the intensity increases more slowly and becomes normal at $570\text{ m}\mu$. There is a discernible drop of intensity in the red sector at about $635\text{ m}\mu$. An extremely weak absorption is also discernible in the green sector at about $545\text{ m}\mu$.

From the observations described above, it would seem that the absence of the yellow region in the spectrum of white light results in enhancing the visual effect of the violet end of the spectrum, so much so that the rest of it, including the blue, green, orange and red sectors, is blocked out or masked and prevented from entering into our visual consciousness. This is a surprising explanation to offer, but no other alternative suggests itself. The suggested explanation is supported by the facts already reported in the case of the "Morning Glory", except that in that case, we are concerned with the extinction of the orange region of the spectrum and an enhancement of the visual effect of the blue sector and the masking or blocking out of the visual effects of the green and red sectors.

Summary

The spectral composition of the colours exhibited by the flowers of *Solanum grandiflorum*, *Nymphaea caerulea* and *Thunbergia grandiflora* has been studied. The results are surprising and an explanation is offered for them in terms of the masking or blocking out of the visual effect of the longer wavelengths in the spectrum by the shorter wavelengths, the necessary condition for which is the removal of the yellow sector, accompanied by a weakening in intensity of the red end of the spectrum.

Floral colours and the physiology of vision— Part VII. The aster and its varied colours

SIR C V RAMAN

(Memoir No. 137 of the Raman Research Institute, Bangalore-6)

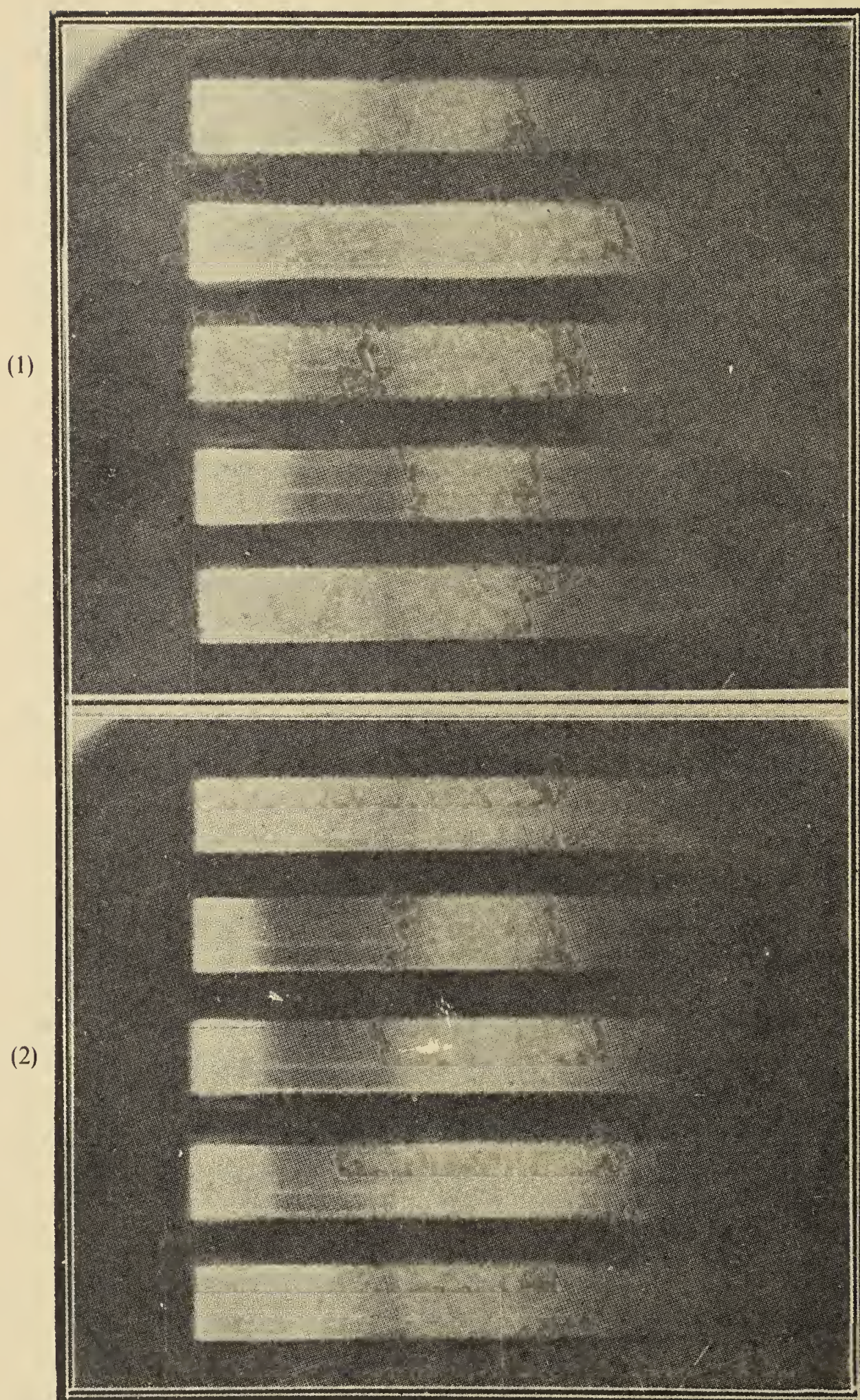
Received June 20, 1963

The findings recorded in the earlier parts of this memoir find a striking confirmation in the results of the studies made with asters of various colours which will presently be described.

The aster is well-known everywhere as one of the most showy of flowering shrubs. Each individual flower with its large feathery head and a gaily-coloured centre is a picture in itself, while the calyx with its numerous leaflets is also a decorative feature. The array of small serrated leaves on the stalk crowned by the flower is not unduly obtrusive and is indeed itself rather attractive. The massing of the blooms on an assembly of stalks growing around a single woody stem makes the whole an impressive floral display.

The opportunity for the present study arose from the fact that asters are grown extensively in and around Bangalore, and being much in demand for decorative purposes are despatched daily to various cities in India and are also marketed at Bangalore. Ample material is, therefore, available for examination. The asters exhibiting marked colour fall clearly into two distinct classes. On sorting out a large quantity of the material, it becomes evident that each class could further be subdivided into three groups, the flowers in each group exhibiting a high degree of uniformity of colour, while those in different groups could be sharply differentiated from each other. Thus, finally the coloured asters could be arranged and listed as follows: Class A: (1) Purple-blue, (2) purple-violet and (3) violet. Class B: (1) Pink, (2) bright pink and (3) rose-red. Spectroscopic examination reveals that class A and class B are totally different in the nature of the absorptions which give rise to their perceived colours, while the three groups in each class exhibit similar features in their spectra, but with very different intensities.

The perceived colours of the asters in class A have their origin in a readily observable extinction of the yellow sector in the spectrum. The absorption exhibits a well-defined edge at about $600\text{ m}\mu$, longer wavelengths having their normal intensities, while the absorption in the region of shorter wavelengths falls off progressively and becomes insensible at about $560\text{ m}\mu$. This absorption is



Figures 1 and 2. 1. Pink aster (with comparison spectra). 2. Purple aster (with comparison spectra).

moderately strong for the asters which appear purple-blue, quite strong for the asters which appear purple-violet and is total for those which appear of a violet colour.

Apart from the strong absorption in the yellow, there are also indications of a minor absorption at $650\text{ m}\mu$ which results in the red sector of the spectrum appearing bifurcated. This is a feature which is just noticeable in the purple-blue asters. But it is more clearly evident with the asters which appear purple-violet and is conspicuous with the asters of a violet colour.

The asters in class B show a spectrum in which the violet, blue, yellow, orange and red sectors in the spectrum appear with their usual intensities, while in the green sector, there is a sensible weakening, especially between 530 and $560\text{ m}\mu$, the maximum of absorption appearing at about $545\text{ m}\mu$. This absorption is noticeable with the pink asters; it is quite strong with those which appear as a bright pink, and nearly complete with the rose-red asters.

Owing to the lack of sensitivity in the green of the available panchromatic films, it is not easy to obtain spectrograms exhibiting the differences between the spectra of the differently coloured asters in a satisfactory manner. Nevertheless, it is possible to show that the differences referred to above exist. Figure 1 in plate I shows three spectra recorded with a pink aster and three different exposures, the first and the last in the group of five spectra being records made for comparison with the light source alone. Likewise, figure 2 in the same plate exhibits the spectra of a purple aster together with comparison spectra recorded in the same manner.

Comparing the spectra appearing in figures 1 and 2 respectively, it will be seen that the absorption appearing in the latter has advanced further to the left towards the red end of the spectrum than in figure 1. Actually, in figure 2, it has covered the yellow sector and there exhibits a sharp cut-off, while in figure 1, the yellow has come through freely, the absorption being only in the green. No other differences between the spectra recorded in figures 1 and 2 are noticeable. In particular, the red and orange regions show relatively to the blue and violet regions of the spectrum, no obvious differences of intensity in the two sets of spectra.

It will be recalled that in the fourth part of this memoir, studies of the pink and purple varieties of the flowers of *Lagerstroemia Flos Reginae* were described, and the differences in their colours were shown to arise in the same manner as in the present case, viz., an absorption of the yellow rays of the spectrum only exhibited by the purple flowers, and an absorption in the green sector shown only by the pink flowers. The differences in colour of the asters in class A and class B though of the same general nature are of a much more striking character, and this may reasonably be ascribed to greater intensities of the absorptions of the respective kinds in the two cases. The question may well be asked, why do the two classes of asters differ so strikingly in their observable colours? A casual observer looking at the flowers would be led to imagine that the asters of class A completely absorb the longer wavelengths in the spectrum and therefore appear blue or violet, while

the asters of class B absorb the shorter wavelengths completely and, therefore, appear red. Actually, in neither case, does any such absorption exist. We are obviously dealing here with an effect of purely physiological origin. It may be suggested that the cut-off of the yellow by the asters of class A results in a suppression of the visual sensations excited by the red and orange sectors of the spectrum. Likewise, when the green is suppressed by the asters of class B, the visual sensations excited by the violet and blue radiations are more or less completely masked by the combined effect of the yellow, orange and red sectors.

Summary

Asters exhibiting vivid colours may be placed in two strikingly contrasted groups, each containing three sub-groups. Spectroscopic examination shows that the perceived colours of one group ranging from purple to violet arise from an extinction of the yellow, while the colours ranging from pink to rose-red of the other group are the result of an absorption in the green.

Floral colours and the physiology of vision— Part VIII. The spectra of the roses

SIR C V RAMAN

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There are hundreds of varieties of roses. Indeed, there is perhaps no flowering shrub which has received more attention from horticulturists who have sought by crossing and intercrossing to create new varieties with specially desired properties, including especially the size and colour of the flowers, the habits of growth of the plant and the frequency of its flowering. It is not proposed in this memoir to deal comprehensively with the subject of the colours of roses. Our aim here is to consider it in its essentials and obtain an insight into the relationship between the spectral composition of the light which has traversed the petals of a rose and its perceived colour.

The variety listed as “Rose Edward” in books on gardening is a great favourite with lovers of roses in India and is known to them more familiarly by the vernacular name of “Gulab”. It grows without trouble, bearing freely and perpetually, the flowers exhaling the sweet scent and exhibiting the soft colour traditionally associated with roses. It is exceedingly vigorous in growth and hence is used as a stock for budding. Standards made with Edward stocks are indeed the most satisfactory and long-lived.

When a petal of “Gulab” is held against the slit of a pocket spectroscope which is directed towards a source of white light, it is seen that the part of the spectrum between 510 and 550 $m\mu$ is much weaker than it normally is in relation to the regions of the spectrum on either side. There is no obvious curtailment of intensity for wavelengths less than 500 $m\mu$ or greater than 570 $m\mu$. In other words, the absorption appears only in the green and does not extend into the regions of other colour on either side. If we view the rose-red glow that penetrates through the flower when it is held in sunlight, the band of absorption is seen very conspicuously and well-defined in its spectrum.

Numerous varieties of roses exhibit colours similar to that of the Gulab but of more saturated hues. Examining the individual petals of such roses through the spectroscope, it is found that as the hue becomes more and more saturated, the absorption band between 510 and 550 $m\mu$ becomes progressively stronger, until finally this region is completely extinguished. There is at the same time an

observable diminution in the intensity of the region of wavelengths between 550 and 590 $m\mu$. It is a surprising fact that even when the colour of such roses is a red of saturated hue, the blue of the spectrum continues to be seen with undiminished intensity.

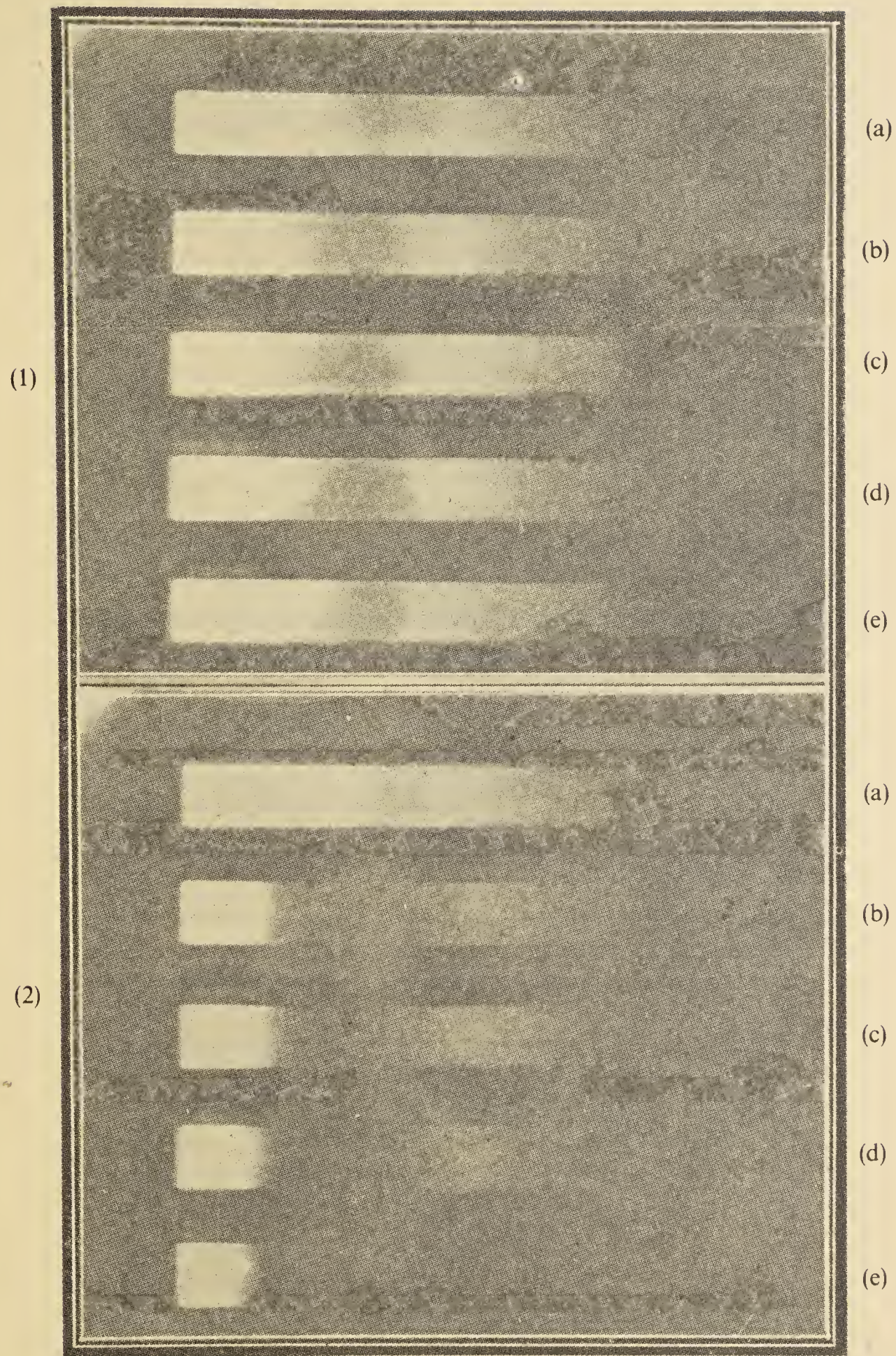
Arising from the facts stated above, two issues emerge which need elucidation. Why is red the dominant colour of roses, despite the presence of the blue and violet regions of the spectrum with undiminished strength? Why does the red manifest itself as a saturated or nearly saturated colour with many roses? In other words, why does not the simultaneous presence of the orange and yellow along with blue and violet result in the presence of a great deal of white light and consequent dilution of the observed colour? It is evident that these issues are of a fundamental nature and that they have to be considered in the light of the facts set out in the earlier parts of this memoir.

That the yellow and orange regions in the spectrum play a dominating role in determining the perceived colours of polychromatic radiation emerged very clearly from the observations with various flowers recorded in the preceding parts of this memoir. Depending on the precise magnitudes and locations of the absorptions in those regions, the perceived colour may be purple, blue, or even violet. The inference is that the removal of the yellow and orange regions which connect the region of longer wavelengths with the rest of the spectrum results in suppressing or masking the sensations excited by the red part of the spectrum, the sensations excited by the blue and violet thereby gaining prominence.

If, on the other hand, the red, orange and yellow sectors of the spectrum are present together, but the green part which links them with the rest of the spectrum is taken out, the sensations excited by the blue and violet regions of the spectrum are wholly or partly masked and the red sensation gains the ascendancy. We have already had illustrations of this effect in the case of the pink blooms of the *Lagerstroemia* and the pink asters. But the roses furnish the most striking examples of the phenomenon.

Figure 1(b), (c) and (d), plate I are the absorption spectra of three rose-petals arranged in the order of increasing depth of their red colour, while (a) and (e) are the spectra of the light-source employed shown for the sake of comparison. It is evident from a comparison of the three spectra that the progressive increase of the depth of the perceived colour is a consequence of the progressive increase in the absorption of the green part of the spectrum, there being no other marked change in the relative intensities of the other parts of the spectrum.

We may now proceed to discuss briefly the spectral characters of the roses of other colours. The efforts of horticulturists have resulted in the development of a great variety of them. One of the most remarkable is that which goes by the name of "Crimson Glory". Examination of the light transmitted by its petals through a spectroscope reveals an extinction of all wavelengths less than 600 $m\mu$ in the spectrum. Figure 2(e) in plate I shows the transmission spectrum of the "Crimson Glory". The petals of a rose exhibiting a scarlet colour likewise showed



Figures 1 and 2. 1. (b) (c) and (d) Absorption spectra of roses: (a) and (e) comparison spectra. 2. (b), (c), (d) and (e) Absorption spectra of roses: (a) comparison spectrum.

no appreciable transparency in the blue and violet regions. But the transmission in the longer wavelength region extended up to $570\text{ m}\mu$. Orange-tinted roses show an observable transmission up to $540\text{ m}\mu$, a band of absorption between 500 and $540\text{ m}\mu$ and a weak transmission of the blue and violet regions of the spectrum. The petals of yellow roses freely transmitted the longer wavelengths in the spectrum up to $500\text{ m}\mu$ but showed a powerful absorption of the blue and violet regions. But this was by no means a perfect extinction unless the light passed through two or more petals in series.

Summary

The characteristic hue designated as rose-red arises from a suppression of the green sector in the spectrum, the radiations of both longer and shorter wavelengths coming through freely. The more complete the absorption of the green is, the more saturated does the resulting hue appear. The reason for the dominance of the red sensation and the saturated hue observed in these circumstances with many varieties of roses is discussed.

Floral colours and the physiology of vision— Part IX. *Hibiscus* and *Bougainvillea*

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By reason of the spectacular character of their displays of colour, as also by reason of their ease of propagation and maintenance, both *Hibiscus* and *Bougainvillea* have attained great popularity as garden plants in tropical and sub-tropical climates. Much attention has been given to these plants by horticulturists at Bangalore to the creation of new varieties exhibiting colours different from those presented by the original species. A wealth of material has in these circumstances, been available to the author for a critical study of the floral colours of both of these plants with the aid of the spectroscope. It is not proposed here to present anything in the nature of a detailed report on the subject. Only a few essential features of interest regarding the general nature of the relationship between the perceived colours and their spectral composition will be set out.

Hibiscus syriacus, so named by Linnaeus, is a species distinct from *Hibiscus rosa sinensis* and is better suited for colder climates. It is however quite at home in the climate of Bangalore. It flowers profusely, its blooms being of a purplish-blue tint which shows up very well against the green foliage of the plant. Figure 1 in the text illustrates the shape of the flower. In view of the findings reported in the previous parts of the memoir, the reader will not be surprised by the statement that the colour of the *Hibiscus syriacus* blooms arises solely by reason of an absorption band appearing in the yellow part of the spectrum. This is so weak that it is barely detectable in the transmission spectrum of a single petal of the flower. But with two petals held together, thereby doubling the absorption path, the cut-off in the yellow shows up clearly.

The spectrograms reproduced as figure 1 in plate I are intended to illustrate the foregoing statements. The red end of the spectrum appears at the left of the picture in each case. Figure 1 (a) and (f) are the spectra of the light source recorded for the purpose of comparison with the other spectrograms which are those of the flower petals of *Hibiscus syriacus*. Figure 1 (b) and (c) are spectra recorded with a single petal and two different exposures, while (d) and (e) were similarly recorded with two petals held together. The absorption band in the yellow which gives rise to the purplish-blue colour of the flower is clearly exhibited in figure 1 (d) and (e).



Figure 1. Flower of *Hibiscus syriacus*.

Hibiscus rosa sinensis is a widespreading shrub with bright shining thick foliage. It is constantly in bloom with large brilliant rose-scarlet flowers which have pretty columns of pistil and stamens projecting from their centres as shown in figure 2 in the text. Spectroscopic examination at first sight suggests that the entire spectrum except the red and orange is cut out by the petals of the flower. A more careful examination reveals, however, that the absorption is complete only in the wavelength range between 500 and 550 $m\mu$, and that there is an appreciable transmission of the blue and violet sectors of the spectrum. These features are shown in the spectrographic records of the transmission by a single petal reproduced as figure 1 (b), (c), (d) and (e) in plate III which were obtained with progressively increasing exposures, figure 1 (a) being a comparison spectrum of the light source employed.

Hibiscus hybrids of the *rosa-sinensis* type are forthcoming in which the flowers have varied colours. The transmission spectra of three of these are reproduced as figure 2(b), (c) and (d) in plate I, these being respectively of red, yellow and orange hybrids, while figure 2(a) and (b) are comparison spectra of the light source. It is significant that the red hibiscus (figure 2 b) shows an absorption only in the green sector of the spectrum, while the blue and violet sectors come through without appreciable loss.

The bougainvilleas are climbing plants which grow vigorously. Their actual flowers are small and inconspicuous, and the decorative value of the plants consists in the fact that the flowers are enclosed in large and brightly coloured

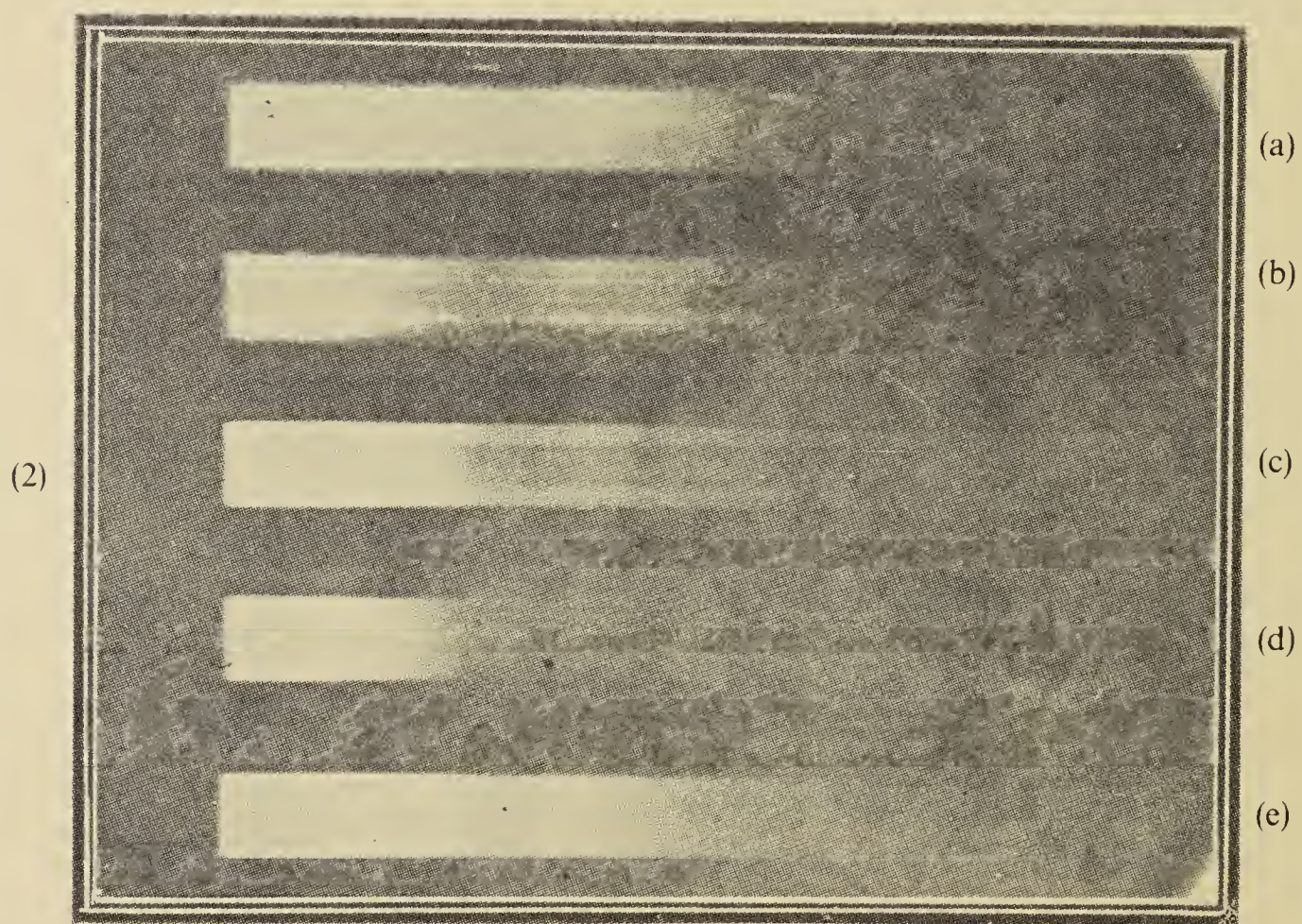
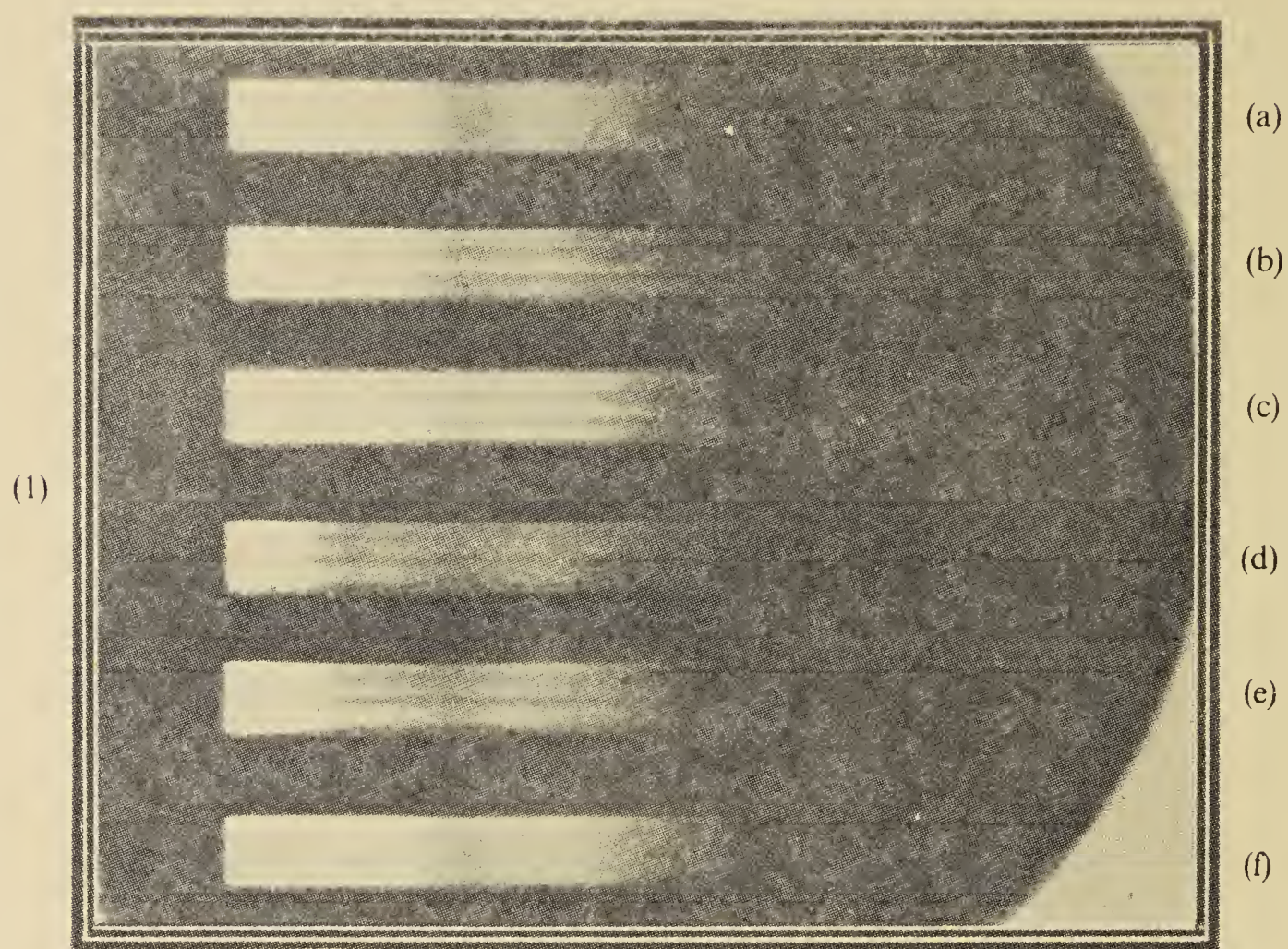


Figure 2. Flower of *Hibiscus rosa sinensis*.

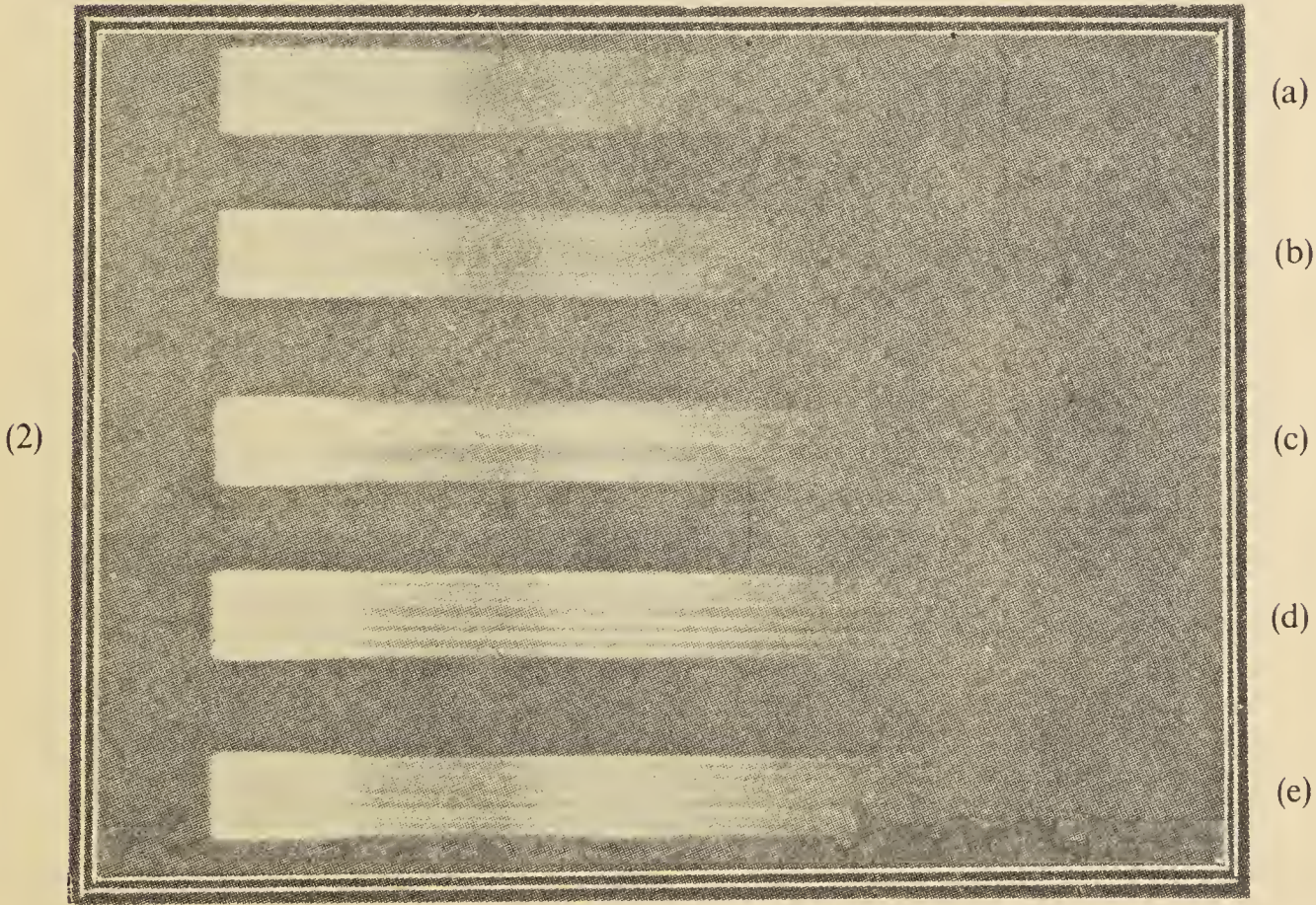
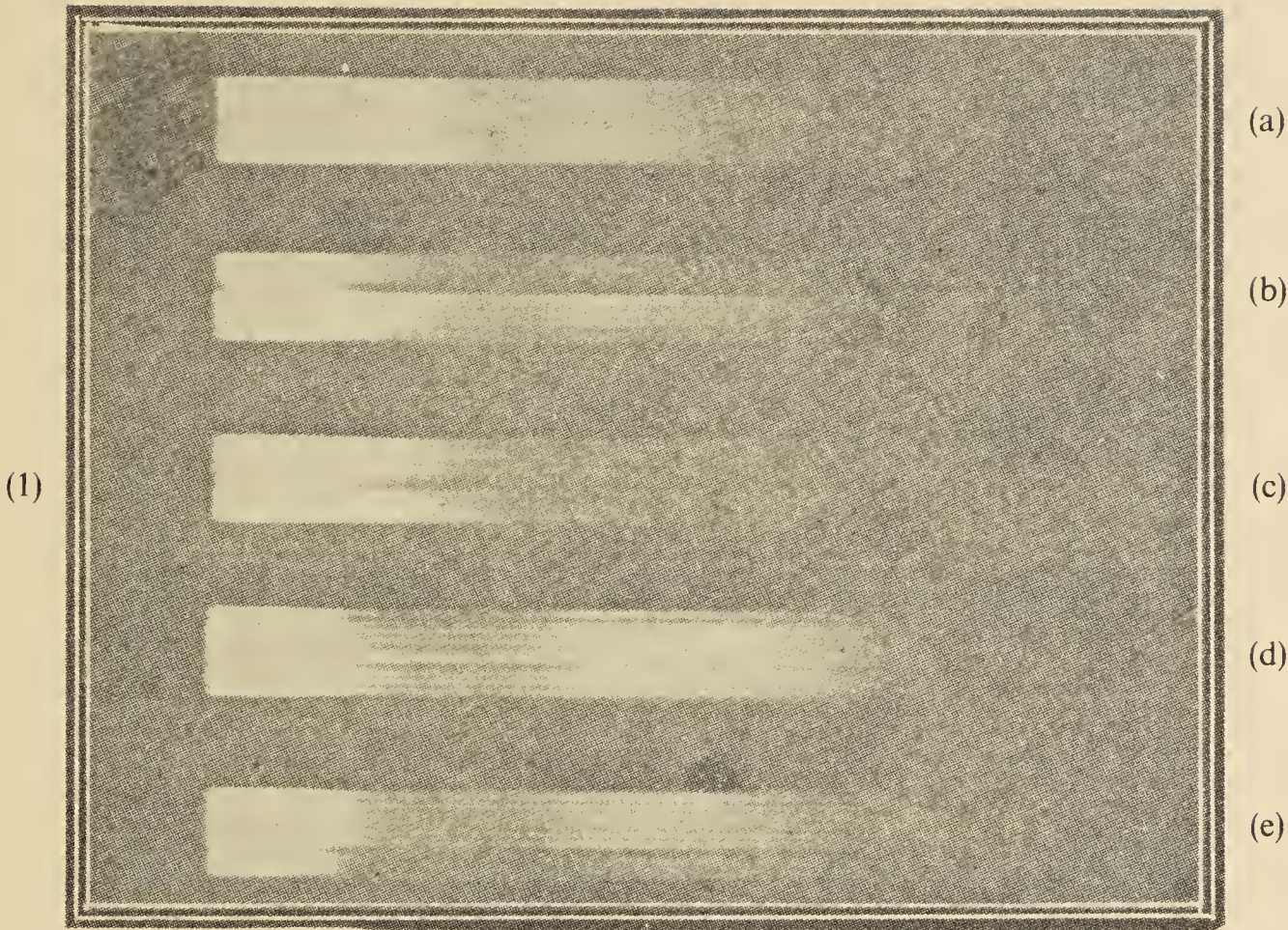
bracts. If allowed to climb up a tree, the bougainvillea rapidly covers it up, so much so that the entire tree appears in due course as a blaze of colour. The number of varieties which have been developed from the naturally occurring species is quite large. Indeed, the collection at the Government Botanic Garden at Bangalore (better known as the Lalbaugh) includes specimens of which the colour exhibited by the bracts bears no resemblance whatever to the original colours. For example, specimens are forthcoming of which the bracts are white, yellow or orange. The bougainvilleas may be classed according to the colour of their bracts into three groups, (a) the purple bougainvilleas, (b) the red bougainvilleas and (c) hybrids exhibiting other colours. We shall comment briefly on the facts revealed by a spectroscopic examination of the available material.

The purple bougainvilleas are characterised by a remarkable degree of transparency of their bracts to the entire visible spectrum *except* in the range of wavelengths between 560 and 590 $m\mu$. Their colour, in fact, is attributable to a specific absorption in this region, in other words, of the yellow sector of the spectrum. The individual varieties, e.g., *Bougainvillea formosa*, which have been developed in which the purple tint is very delicate, show this absorption only weakly, whereas it is highly pronounced in those exhibiting purples of saturated hues.

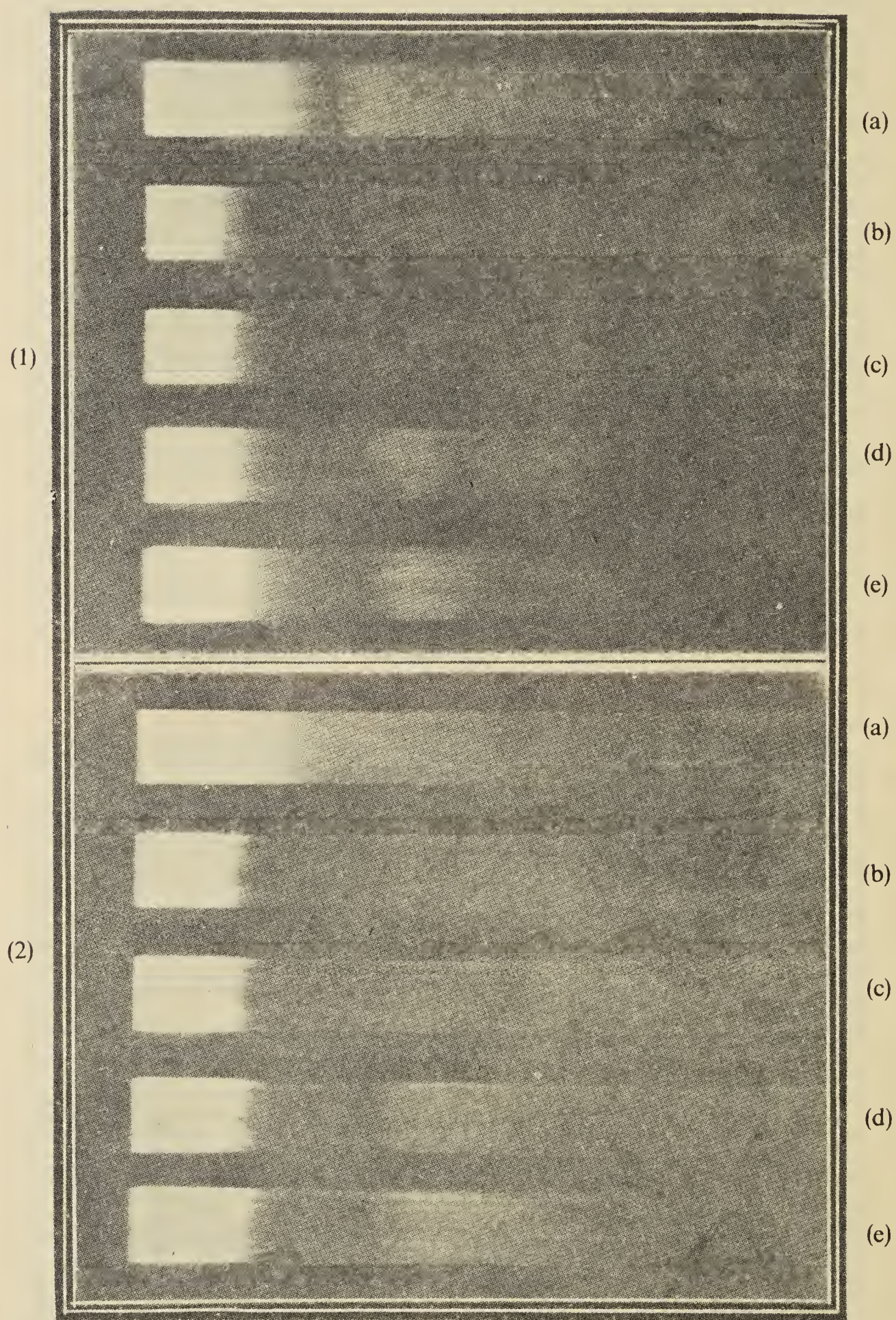
The red bougainvilleas owe their colour to an absorption which manifests itself in the wavelength range between 500 and 560 $m\mu$, in other words, covers the green sector of the spectrum. The blue and violet sectors are however transmitted more



Figures 1 and 2. 1. Spectra of *Hibiscus syriacus* with comparison spectra. 2. Spectra of *Hibiscus* hybrids with comparison spectra.



Figures 1 and 2. 1. Spectra of Purple *Bougainvilleas*. 2. Spectra of other *Bougainvilleas*: (d) rose-red; (e) deep red.



Figures 1 and 2. 1. Spectra of *Hibiscus rosa sinensis* with comparison spectrum. 2. Spectra of Pomegranate flower with comparison spectrum.

or less freely. The spectroscopic behaviour of the red bougainvilleas thus resembles that of the red roses. Indeed, some of the most spectacular of the bougainvilleas are those in which the absorption of the green sector is not quite complete and hence the bracts exhibit a brilliant colour resembling that of roses.

The hybrid varieties exhibiting other colours show absorption spectra of other types. It will suffice here to mention the behaviour of an orange-coloured bougainvillea. Its bracts exhibit a cut-off of the violet and blue sectors, with the result that a well-defined absorption edge appears at $500\text{ m}\mu$ separating the regions of smaller and greater wavelengths. An absorption is also noticeable in the green sector, but this is much feebler.

Figure 1(b), (c), (d) and (e) in plate II are the transmission spectra of four purple bougainvilleas arranged in the order of increasing saturation of the hues exhibited by them. The low photographic sensitivity of the panchromatic film in the green of the spectrum is very evident in figure 1(a) which is a comparison recorded with the light-source employed. The dark band in the green thus resulting also appears in the four other spectra recorded with the bracts. This tends to obscure the fact that the purple bougainvilleas have no absorption in the green of the spectrum. The absorption appearing in the yellow and its increasing strength in the series can, however, be recognised in the spectra.

Figure 2 shows alongside a comparison spectrum of the source [figure 2(a)], the spectra of four other bougainvilleas. Figure 2(d) which is the spectrum of a bright-red bract and figure 2(e) of a bract of a deeper red colour are particularly significant. They exhibit the very interesting feature that the green of the spectrum is absorbed very strongly by these bracts, while the blue and violet of the spectrum are transmitted more or less freely.

Summary

The spectroscopic behaviours of the flowers of *Hibiscus syriacus* and *Hibiscus rosa sinensis* are quite different. The purple colour in the former case is due to an absorption in the yellow and the red in the latter to an absorption in the green. The purple and red varieties of *Bougainvillea* show differences of the same general nature and having a similar origin.

Floral colours and the physiology of vision— Part X. Flowers exhibiting band spectra

SIR C V RAMAN

(Memoir No. 137 of the Raman Research Institute, Bangalore-6)

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In earlier parts of the memoir, we have already encountered several cases in which the absorption of the flowers manifests itself as a single dark band and others in which it appears as two dark bands in regions not very remote from each other in the spectrum. In the present part of the memoir, we shall concern ourselves with particular cases which came to light in the course of the author's studies and in which the absorption exhibits a sequence of fairly well-defined dark bands traversing the spectrum in an ordered succession. The origin of these band-systems is obviously a matter of considerable interest. But we shall concern ourselves principally with the relation between the observed positions of the absorption bands and the colour manifested by the flower to our visual perceptions.

We shall commence with the case of the flowers of the twining creeper *Clitoria ternatea* exhibiting a bright blue colour. Figure 1 (b) in the text illustrates the shape of the flower, the blue colour appearing all around its extended margin. The absorption spectrum of the flower recorded with three different exposures are reproduced in figure 2 in plate I, alongside of the two comparison spectra of the light-source appearing at the top and bottom of the figure. Three dark bands can be seen in the spectrum; their centres being located respectively at about 630, 575 and 525 m μ . The first of the three bands appearing in the orange-red is the most intense, the second in the yellow is less intense but is also fairly well defined, while the third band in the green is both weak and diffuse. The striking blue colour exhibited by the flower is evidently ascribable principally to the intense bands appearing at 630 and 575 m μ .

The second case we shall consider is that of the flowers of the ground orchid known as *Aerides multiflorum* whose flowers are located in considerable numbers along elongated stems which emerge from the plant alongside of its leaves. The shape of the individual flower and of the stalk carrying it is shown in figure 1 (a) in the text. The flowers have a vivid purplish-red colour. The absorption spectrum responsible for this hue has been recorded with three different exposures in figure 1 in plate I, following which a comparison spectrum of the light-source is

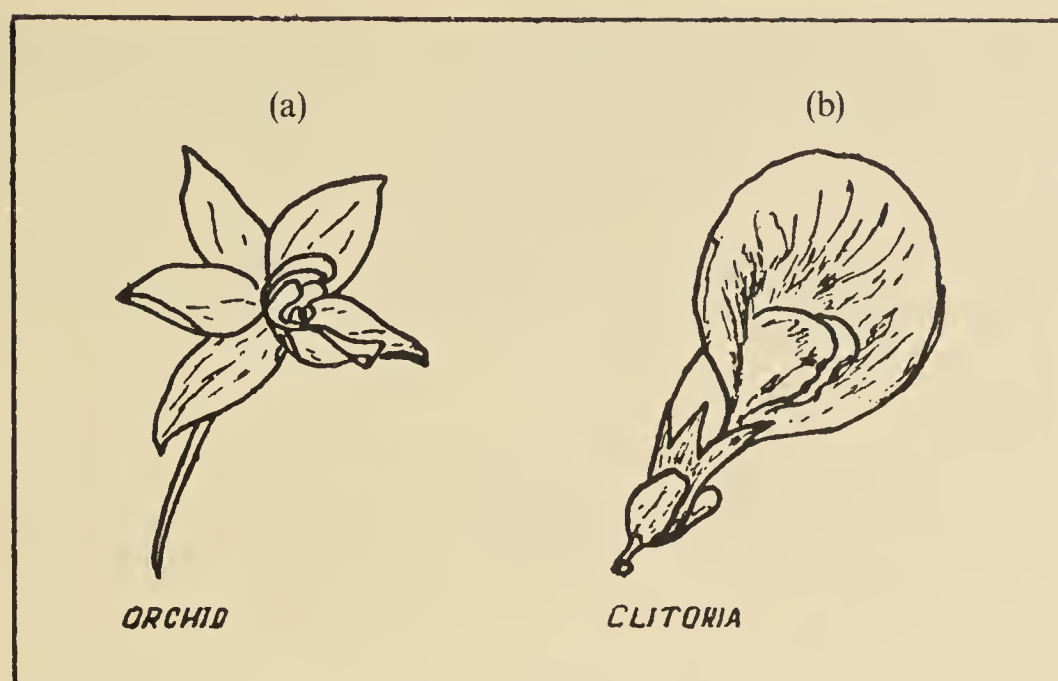


Figure 1. Flowers of *Aerides multiflorum* (a) and *Clitoria ternatea* (b).

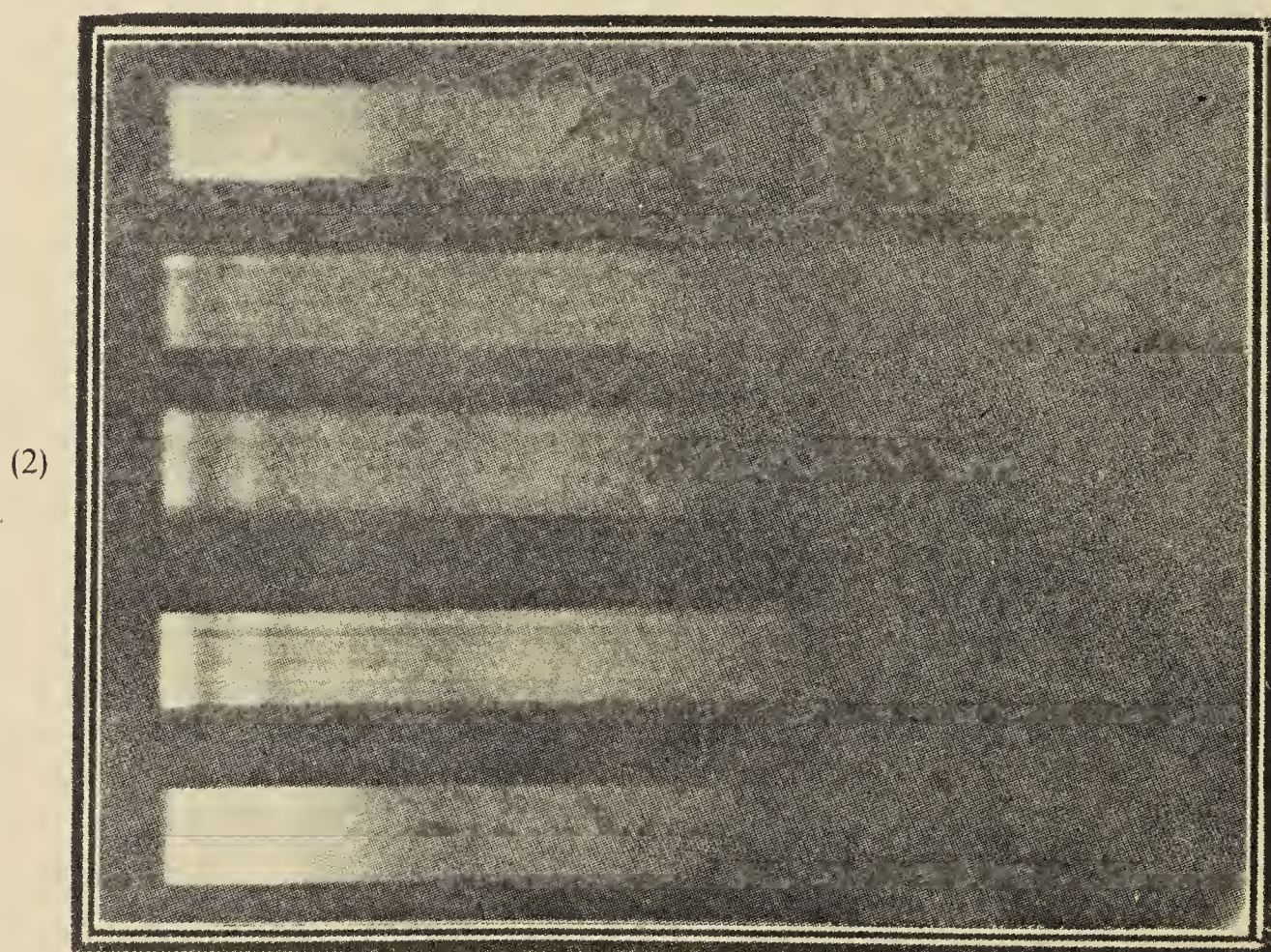
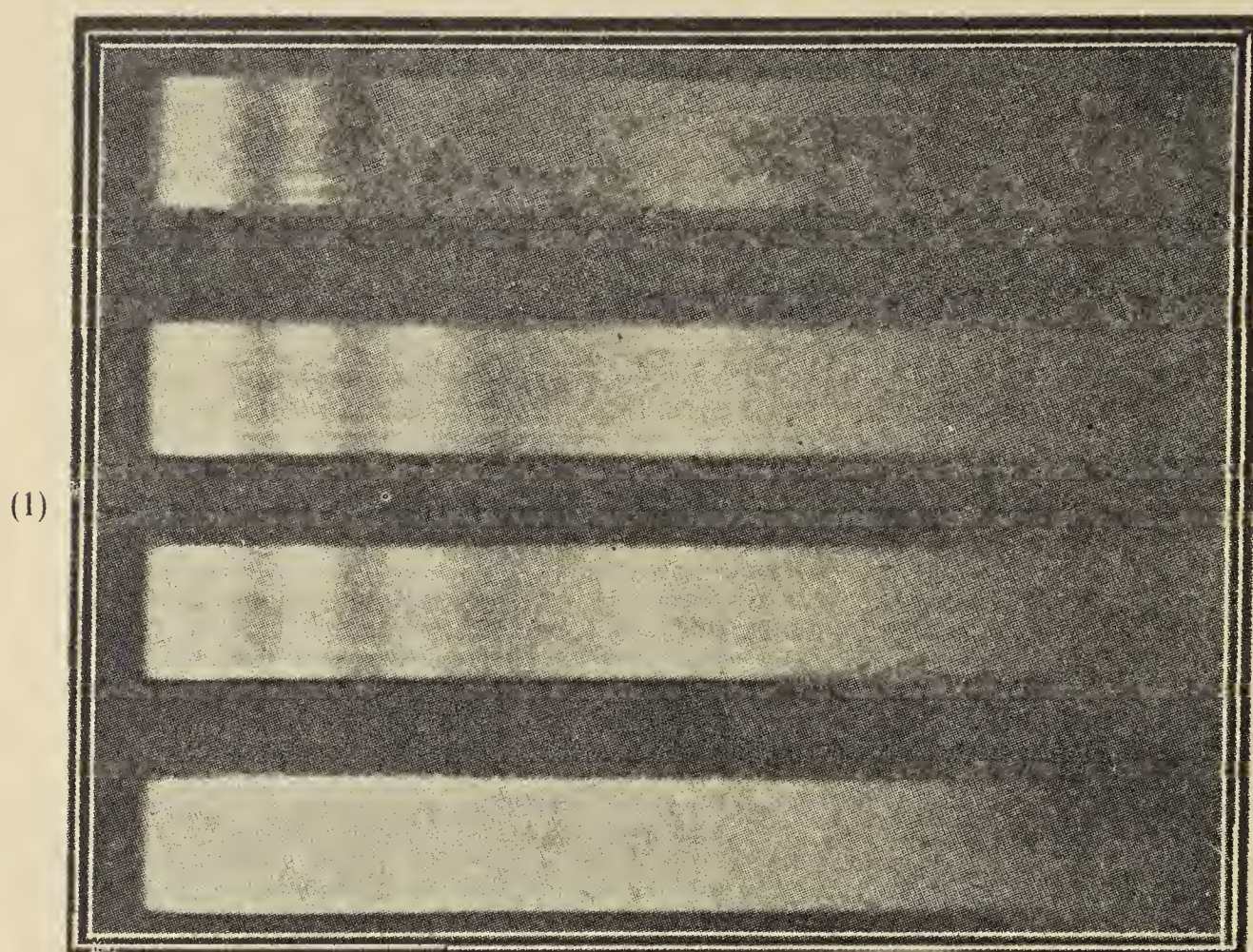
also shown. Three dark bands are exhibited, the first two located at 590 and 545 $m\mu$ being particularly intense and well defined, the third band at 505 $m\mu$ being both weak and diffuse.

Another orchid which shows a similar absorption is known as *Aerides crispum*. This bears flowers in great numbers along arching spikes. A front and a back view of the individual flower is shown in figure 2 below in the text. Part of each flower exhibits a purplish-red hue and the absorption spectrum of this region as seen visually is very similar to that represented in figure 1 in plate I. Two other orchids bearing purple flowers, viz., *Spathoglottis plicata*, and *Cattleya* (hybrid species) also exhibit similar spectra.

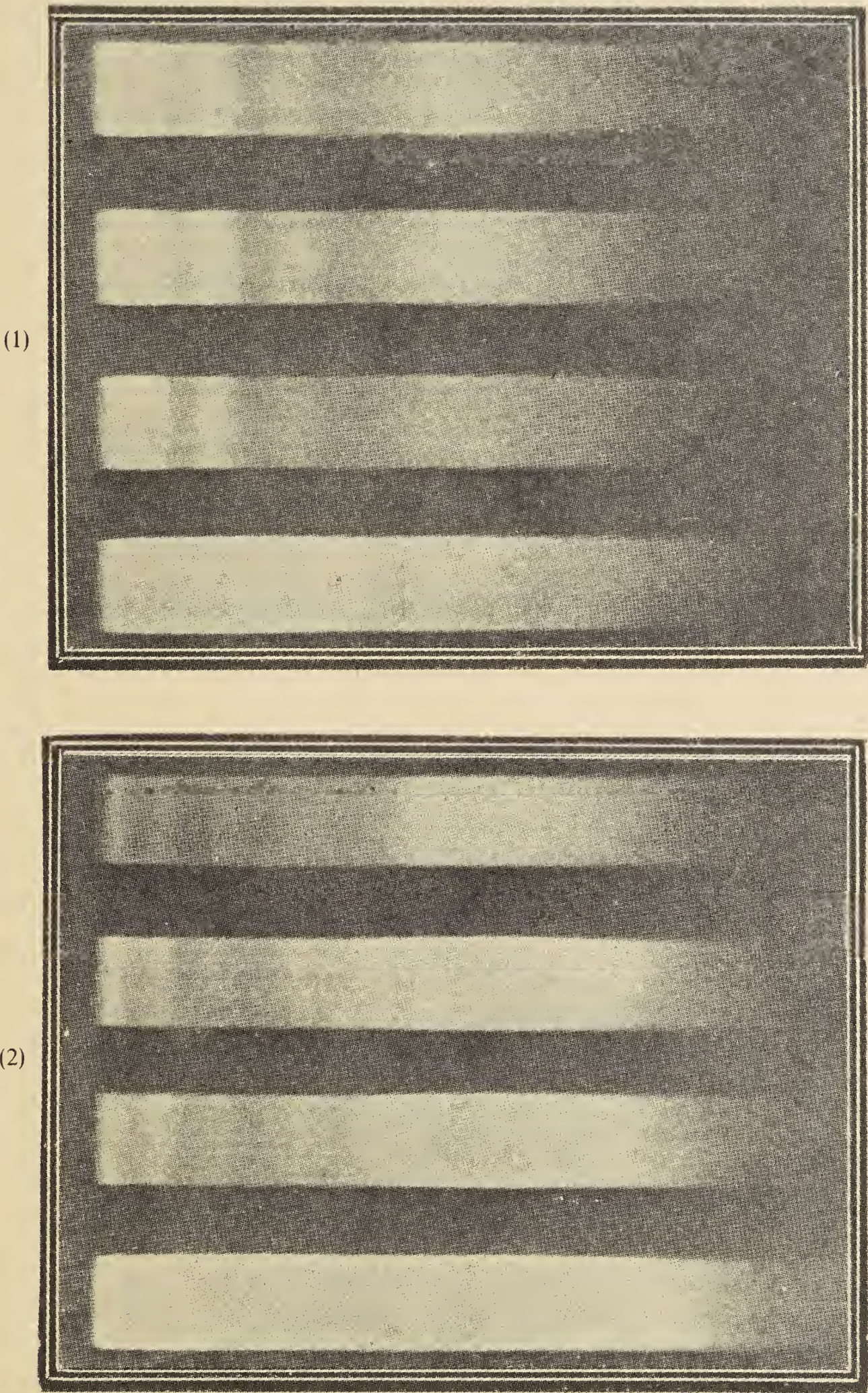
The garden plant known as *Cineraria* is usually grown in pots and its flowers exhibit a wide range of beautiful colours. The absorption spectrum of the petal of a flower exhibiting a purplish-red hue recorded with three different exposures is reproduced as figure 1 in plate II, while that of another flower exhibiting a deep blue is similarly shown in figure 2 in the same plate. A comparison spectrum of



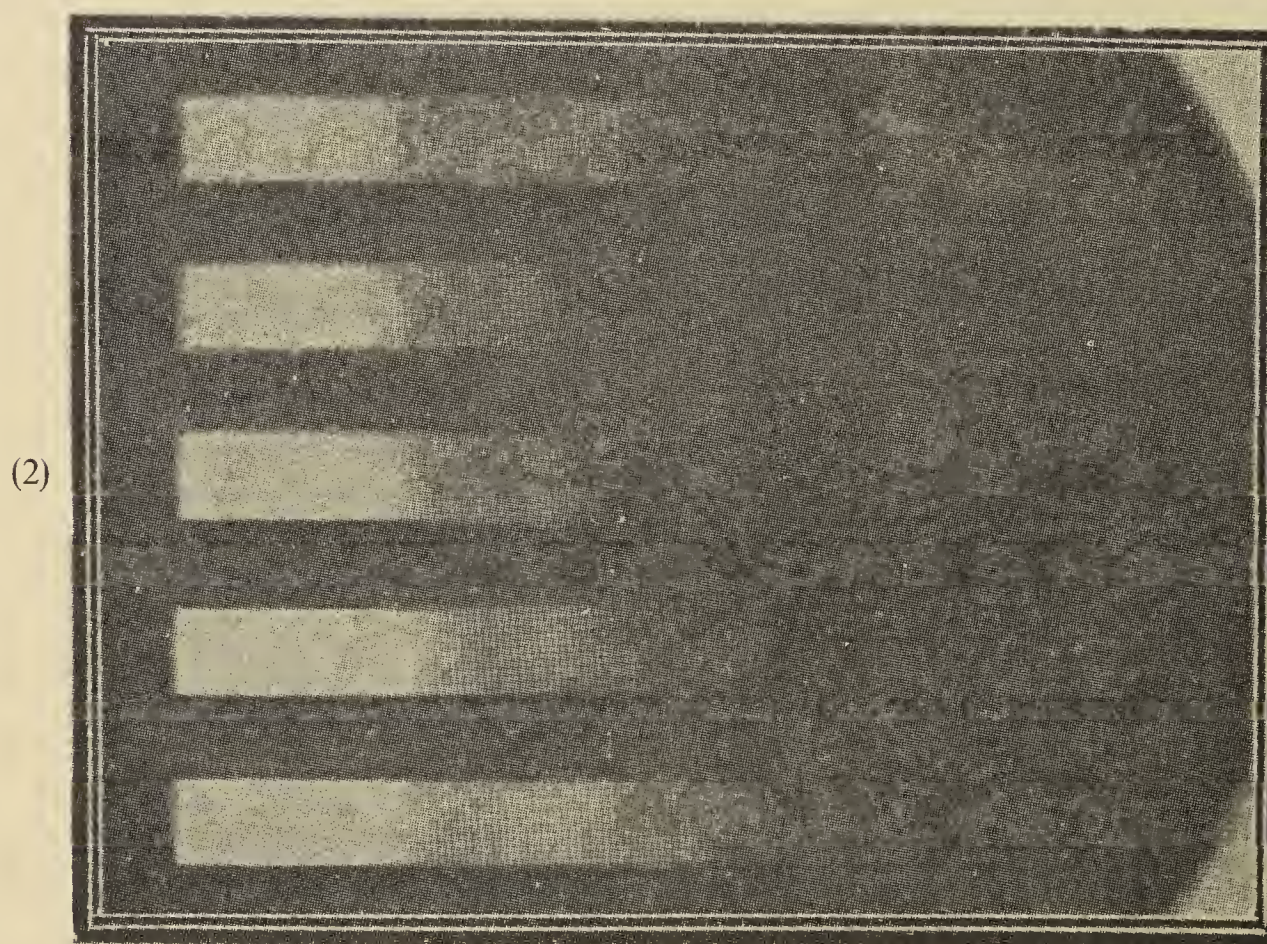
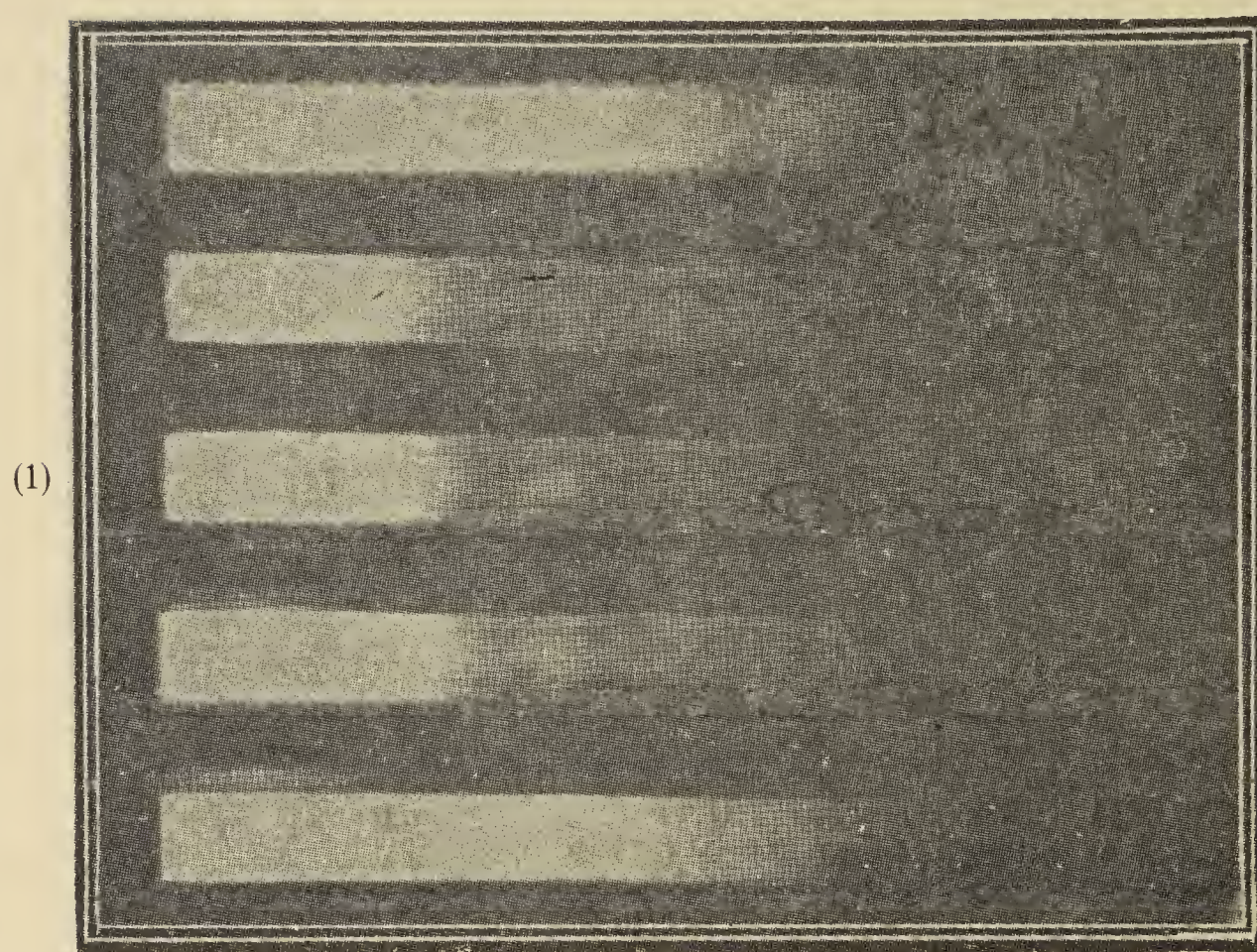
Figure 2. Flower of *Aerides crispum* (front and back views).



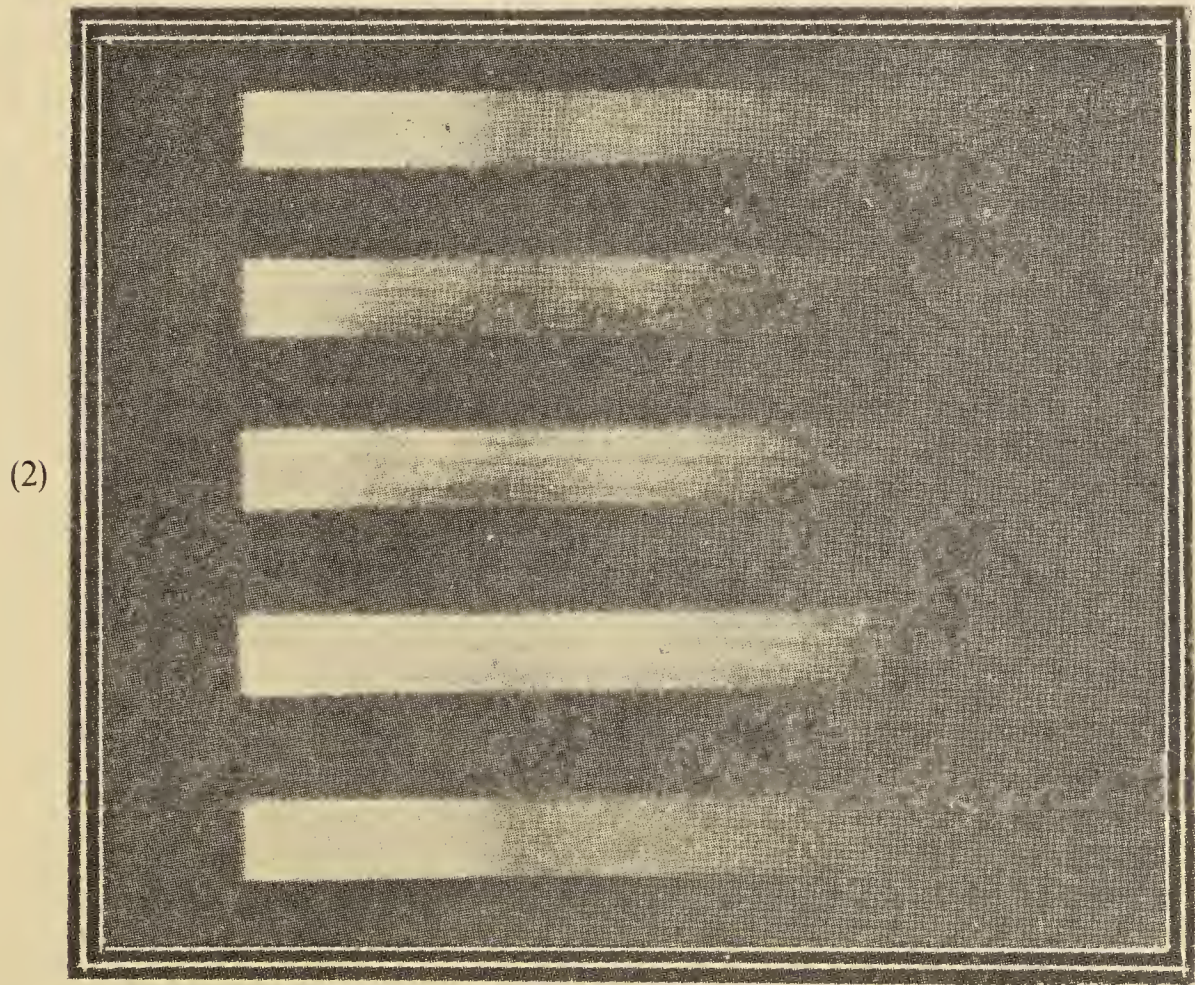
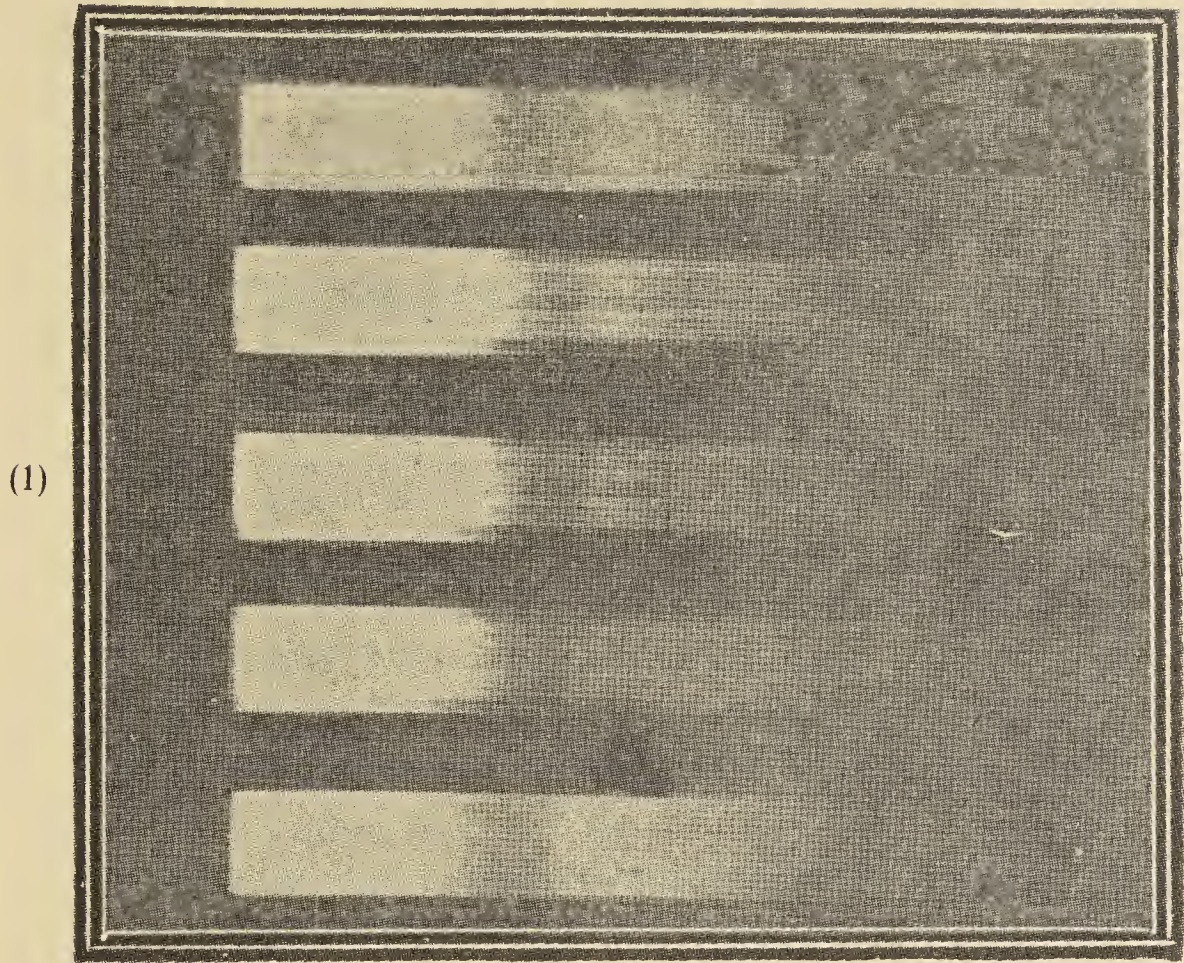
Figures 1 and 2. 1. Absorption spectrum of *Aerides multiflorum* with comparison spectrum.
2. Absorption spectrum of *Clitoria Ternatea* with comparison spectra.



Figures 1 and 2. 1. Absorption spectrum of *Cineraria* flower (purplish-red) with comparison spectrum. 2. Absorption spectrum of *Cineraria* flower (deep blue) with comparison spectrum.



Figures 1 and 2. 1. Absorption spectrum of *Allamanda grandiflora* with comparison spectra.
2. Absorption spectrum of *Clitoria ternatea* with comparison spectra.



Figures 1 and 2. 1. Absorption spectrum of *Peltorum ferrugineum* with comparison spectra.
2. Absorption spectrum of *Oxalis acetosella* with comparison spectra.

the light source is shown below the three spectra of the flower in each figure. The striking similarity of the spectra shown as figure 1 in plate I and as figure 1 in plate II is noticeable. Likewise, figure 2 in plate I and figure 2 in plate II also exhibit a general similarity. These resemblances are not surprising in view of the fact that the observed colours in these cases are much like each other.

We shall proceed to consider some flowers which also exhibit band spectra in absorption, but in an altogether different part of the spectrum. Many trees, shrubs and climbing or twining plants have flowers exhibiting yellow hues, ranging from a pale straw-yellow to the deepest golden-yellow. In all these cases, it is evident on inspection that the petals exercise an absorption in the violet and blue sectors of the spectrum, the stronger such absorption is and the further it extends into the blue, the more intense the colour exhibited. Indeed, unless the yellow hue of the flower is of the palest, the absorption extends up to $500\text{ m}\mu$, thus covering the violet and blue completely; if the absorption is sufficiently intense, something in the nature of an absorption edge may be noticed at about $510\text{ m}\mu$. The individual petals of a flower are usually fairly thin, and it is therefore not to be expected that the extinction of the blue and violet regions would be total. Indeed if we make the observations in bright sunlight, we may expect to see a part of the blue in the spectrum coming through and this is indeed actually the case with many flowers, e.g., the gorgeous golden-yellow blooms of *Allamanda grandiflora*, the bell-shaped flowers of *Thevetia neriifolia* (the yellow oleander), the yellow panicles of the avenue tree *Peltoforum ferrugineum*, and so on. The photographic record of the spectrum extending to wavelengths shorter than $500\text{ m}\mu$ made with adequately long exposures with these flowers exhibits a succession of dark bands.

Figure 1 in plate III shows this effect observed with *Allamanda grandiflora*. Figure 2 in the same plate shows the succession of bands observed with *Thevetia neriifolia*. The panicles of *Peltoforum ferrugineum* are very thin and it is therefore not surprising that they pass the blue of the spectrum rather freely and that the bands in this region are therefore recorded easily. Figure 1 in plate IV shows these features.

It is clear from the similarity of the features observed in the spectra of several different plant species that the band-structure is a specific property of the absorbing material present in the petal. In the case of the yellow flowers, this is presumably a carotenoid pigment.

Summary

The absorption spectra of the blue flowers of *Clitoria ternatea* and of the purplish-red flowers of the orchid *Aerides multiflorum*, have been recorded. They show a striking similarity with the absorption spectra of the petals of *Cineraria* exhibiting those colours. Various yellow flowers exhibit a banded structure in the blue-violet regions of the spectrum which they only feebly transmit.

Floral colours and the physiology of vision— Part XI. A review of the results

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The special role played by the yellow sector of the spectrum between 566 and 589 $m\mu$ in the physiology of vision is a fact of observation which emerges very clearly from the studies described in this memoir. The sensory impression produced by the ensemble of polychromatic radiations which form the visible spectrum is profoundly influenced by this range of wavelengths if present, and is modified in a remarkable fashion when it is removed or weakened by absorption. A further result established by the study is that, in general, the sensory impression produced by polychromatic radiation can by no means be described as the result of a simple superposition of the effects of the individual parts of the ensemble. The weakening or even complete suppression of the effects of some parts of the spectrum by those of the others in certain circumstances is a fact of observation. We shall deal with these matters in some detail, confining ourselves to a statement of what is actually observed in various cases.

The region of the yellow in the spectrum of polychromatic radiation makes its presence felt in the colours of the leaves and flowers of numerous plants. Indeed, in a great many cases, it is the colour which is actually perceived. Spectroscopic examination reveals that yellow of a richer hue is observed when the violet and blue sectors appearing between 400 and 500 $m\mu$ are completely eliminated, while the rest of the spectrum is freely transmitted. If, on the other hand, there is also a sensible transmission of wavelengths less than 500 $m\mu$, the colour perceived is a paler yellow. As an illustration of a flower exhibiting the richer hue, we may mention the shrub *Caesalpinia pulcherrima*, one of the two known varieties of which bears a profusion of vividly coloured yellow flowers. The absorption spectrum of a petal of this variety is reproduced as figure 1 in plate I along with comparison spectra of the light-source employed. The cut-off in the spectrum covers not only the violet and the blue, but also the green up to 520 $m\mu$.

As the violet and blue sectors of the spectrum are of low luminous efficiency, it is not surprising that their elimination has but little effect on the brightness of flowers. Indeed, yellow flowers are usually quite brilliant. It is significant that even when most of the green sector is cut out, this continues to be the case. An

excellent illustration of this is furnished by the flowers of the shrub *Calendula*, the petals of which absorb the violet and blue and also the green completely up to $550\text{ m}\mu$, while the rest of the spectrum is unaffected. The flowers appear of a bright orange-yellow hue. We may compare them with those of the well-known tree *Cordia sebestina* which bears showy clusters of flowers of a rich orange hue. The violet, blue and green sectors of the spectrum are completely cut out by the petals of this flower, while the yellow sector from 565 to $590\text{ m}\mu$ is enfeebled. The striking difference in colour as well as its diminished brightness as compared with the flowers of *Calendula* are clearly due to the partial elimination of the yellow radiations. A more complete elimination of the yellow sector results in a further striking change of colour from orange to red coupled with a further enfeeblement of luminosity. This is well illustrated by the flowers of the second known variety of *Caesalpinia pulcherrima* as well as by the flowers of numerous other trees and shrubs.

The highly remarkable fashion in which the yellow sector of the spectrum influences our visual perceptions of light and colour becomes evident when we study various cases in which that sector is partially or wholly excluded by absorption. As has been shown in the second part of this memoir, the familiar green colour of vegetation arises in that fashion. To convince himself of this, an observer may compare the spectra of sunlight filtering through two leaves of the same tree held side by side, one of them being a mature green leaf and the other a leaf which has turned a golden-yellow prior to its falling off. Alternatively, he may view a green field filled with growing young plants through a pocket spectroscope and compare it with the spectrum of the sky above it as seen through a yellow filter which cuts out the blue and the violet. The visible range is the same in the two cases, viz., 510 to $650\text{ m}\mu$, but the spectroscope reveals the weakening or elimination of the yellow sector in the spectrum of the green leaves. Indeed, it is clear from such observations that our perception of the green colour results from the elimination of the yellow sector. It is also evident that when the yellow is eliminated, the visual effect of the green masks or suppresses the visual sensation due to the red which is already weakened to some extent in the spectrum of the green leaves.

Another highly noteworthy phenomenon discovered in the present investigation is that when the yellow sector in the spectrum of white light is weakened or wholly eliminated, the polychromatic radiation which is left over manifests itself to our visual sensations as exhibiting a *purple* colour. Several examples of flowers exhibiting this effect have been given in the earlier parts of the memoir. Perhaps the most striking case is that of the flowers borne by one variety of the tree *Lagerstroemia Flos Regina* described in the fourth part of the memoir. The purple colour of its petals is a conspicuous phenomenon and is indeed responsible for the magnificent appearance presented by this great tree when it is in full flower. As the purple colour of each flower in a bunch fades away day after day, so also does the absorption in the yellow which is its origin.

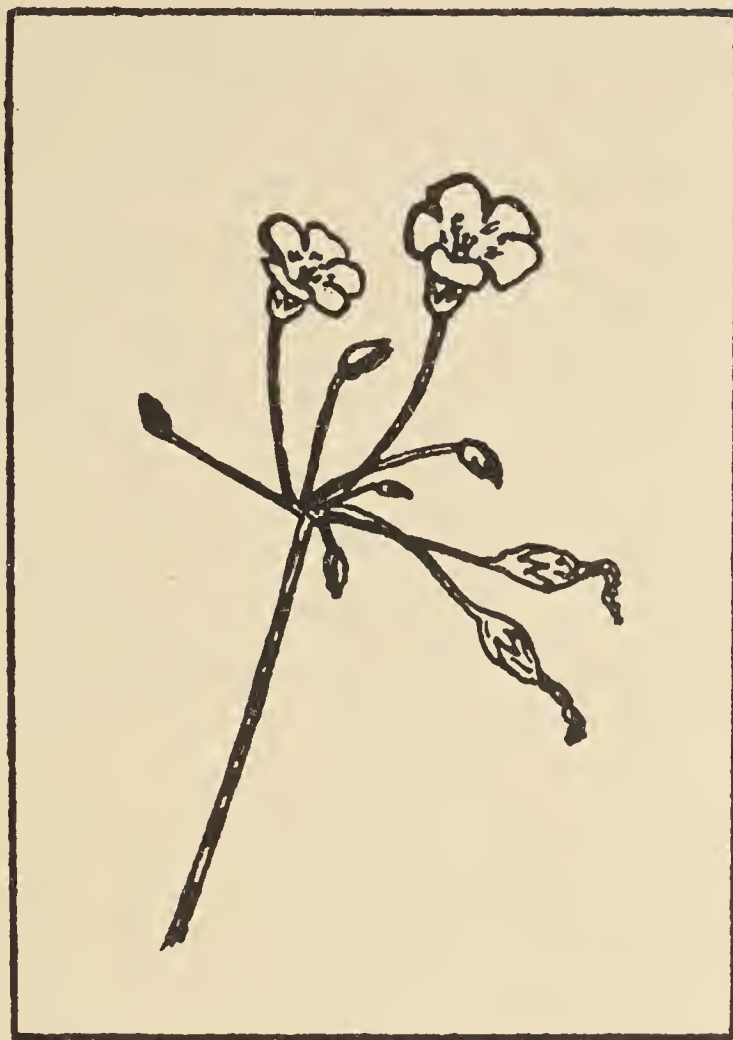


Figure 1. Flowers of *Oxalis acetosella* (reddish-purple).



Figure 2. Flower of *Barleria gibsonii* (azure-blue, also reddish purple).

A long list could be compiled of flowers which exhibit a purple colour by reason of the partial or complete extinction of the yellow by absorption. The depth or degree of saturation of the purple hue is found to depend greatly on the strength of such absorption. It will suffice here to mention a few examples. The common weed known botanically as *Oxalis acetosella* bears small reddish-purple flowers which very clearly exhibit the absorption in the yellow, as is shown in the spectra reproduced as figure 2 in plate IV of part X of the preceding part of the memoir. The garden plant, known familiarly as *Balsam* and botanically as *Impatiens*, is another illustration. There are numerous known varieties of balsam, in some of which the flowers exhibit a purple colour. The balsam flowers which are a vivid purple exhibit a complete extinction of the yellow, the band of absorption covering the entire region of wavelengths between 590 and 550 m μ . Figure 1 in plate II reproduces this effect. Other varieties of balsam in which the purple is less vivid also exhibit the absorption in the same region of the spectrum but less strongly.

Another result of great interest which has emerged from the present investigation relates to the origin of the blue colour exhibited by numerous flowers. In every case of the kind which has been studied, it is found that the yellow sector in the spectrum has either been completely eliminated or else has been greatly weakened by absorption. Indeed, that a definite relationship exists between the depth of the blue colour and the strength of the absorption in the yellow is indicated by the cases studied.

To the numerous examples of blue flowers of which the spectroscopic behaviour has been discussed earlier in the memoir, we may add yet another. This is the shrub *Plumbago capensis* which is a very attractive hedge-plant bearing a profusion of pale blue flowers all the year round and is a familiar sight in Indian gardens (figure 3 in the text). The absorption of the yellow by its flowers is weak and is only just noticeable in the spectrum of the light transmitted by a single petal. But when we hold a few flowers together, the blue colour of the light which penetrates through the mass becomes conspicuous. Examining this light through a pocket spectroscope, a well defined absorption band can be seen in it in the yellow, still another band in the red and a fainter band in the green.

The intense blue of the cornflower (*Centaurea cyanus*) presents a striking contrast with the pale blue of *Plumbago capensis*. The spectroscope reveals the origin of its colour to be an intense absorption band covering the spectral region from 560 to 620 m μ , in other words, both the yellow and the orange sectors of the spectrum. But the rest of the spectrum, including not only the violet and the blue but also the green and red sectors, does not manifest any weakening by absorption. Thus, the chromatic behaviour of the blue cornflower closely parallels that of the "Morning Glory" or *Ipomea learii* discussed in the third part of this memoir. That in these cases, the colour of the flower appears to our perceptions as a saturated blue must be considered highly remarkable. The only possible interpretation of the facts of observation appears to be that in these



Figure 3. Flowers of *Plumbago capensis* (azure-blue).

cases, the visual sensation excited by the unextinguished red as well as the entire green of the spectrum is masked or suppressed by the sensations excited by the blue and violet sectors.

Why the extinction of the yellow sector has the effect of exciting a *purple sensation* in the case of some flowers, while in other cases the observed result is a *blue sensation*, is an issue which obviously needs elucidation. An answer to this question is forthcoming in terms of the observed spectroscopic behaviour of the flowers themselves. A "purple" sensation is evidently one in which the observer is conscious simultaneously of the visual effects of the two parts of the spectrum lying on either side of the maximum of luminous efficiency in the yellow. Indeed, that the extinction of the yellow sector should result in exciting the sensation of "purple" is not altogether surprising. But if the extinction of the yellow be accompanied by other changes in the distribution of intensity in the spectrum, the sensation of "purple" may be modified in the sense that the sensory effect of the part of the spectrum on one side may dominate over the sensory effect of the part of the spectrum on the other side and may even mask or suppress it altogether. In



Figure 4. Flowers of *Phlox drummondii* (various colours).

other words, we may have a “purple” in which the red is dominant or a “purple” in which the blue is dominant and may indeed be the colour that is actually perceived.

It will suffice here to mention three cases illustrative of the remarks made above. The first is that of the well-known garden shrub *Phlox drummondii* (figure 4 in the text). This has numerous varieties exhibiting colours and colour patterns of various sorts in its flowers. To the spectroscopist, the examination of these varieties with a view to ascertain how the spectral composition of the floral colours determines their physiological impact in an interesting exercise. Two of the flowers of *Phlox* examined by the author showed highly contrasting characters, one of them appearing a rich red and the other a purplish-blue. Closer examination, however, indicated that they should both be classed as “purples”, but of different sorts. The characteristic absorption band in the yellow was exhibited by both, but the red end of the spectrum appeared more intense with one and relatively weak in the other, evidently as the result of a specific absorption effective at that end.

Still another example is furnished by the flowers of the shrub *Barleria* which is a common sight in Indian gardens. The shrub bears azure-blue flowers, while another variety bears reddish-purple flowers. In both cases, the colour is primarily ascribable to an absorption of the yellow portion of the spectrum, the



Figure 5. Flowers of *Achimenes grandiflora* (purplish blue, also purplish red).

differences being in the relative intensity of the blue and red sectors of the spectrum.

The third example we shall mention is that of the garden shrub *Achimenes grandiflora* which bears a profusion of flowers of large size. These are justly admired for their beauty of colour (*see* figure 5 in the text). A purplish-blue is the most frequently exhibited hue, but there is also a variety which bears flowers of a red colour. Flowers of both sorts show the absorption in the yellow characteristic of "purple" flowers. In both cases also, the red end of the spectrum is conspicuous. But it is much more brilliant in the case of the red than with the blue flowers.

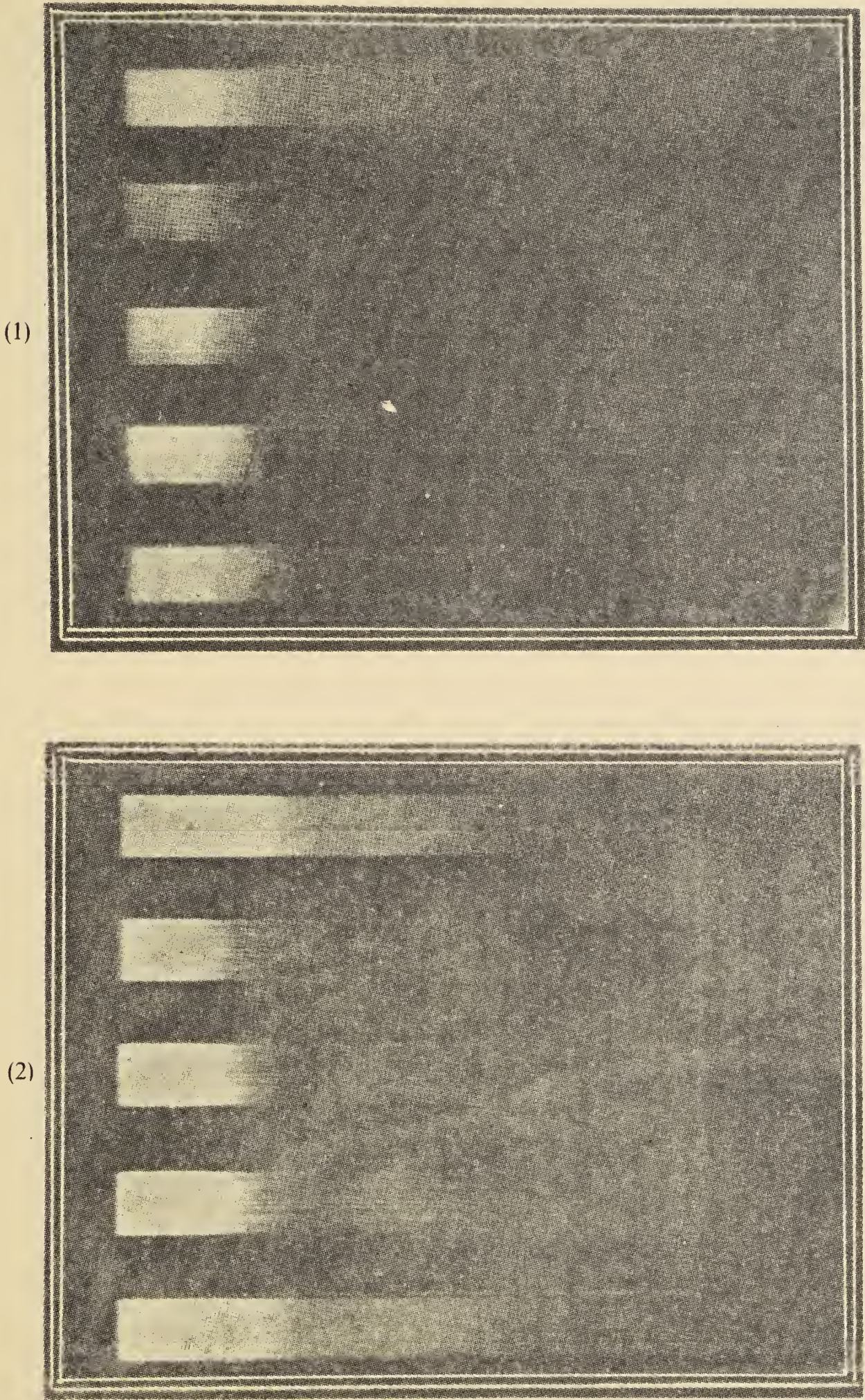
The pomegranate flower illustrated in figure 6 in the text has six petals which are of a rich orange-red hue. Spectroscopic examination of the light which penetrates through them shows that the range of wavelengths between 490 and 550 $m\mu$ (in other words, the green sector of the spectrum) is extinguished by absorption, but that the spectral regions on either side of this absorption band are transmitted more or less freely. The wavelengths less than 590 $m\mu$ show some weakening of intensity, while still greater wavelengths show no indications of such weakening. The observed colour of the petals is thus satisfactorily accounted



Figure 6. Flower of the pomegranate tree (orange-red).

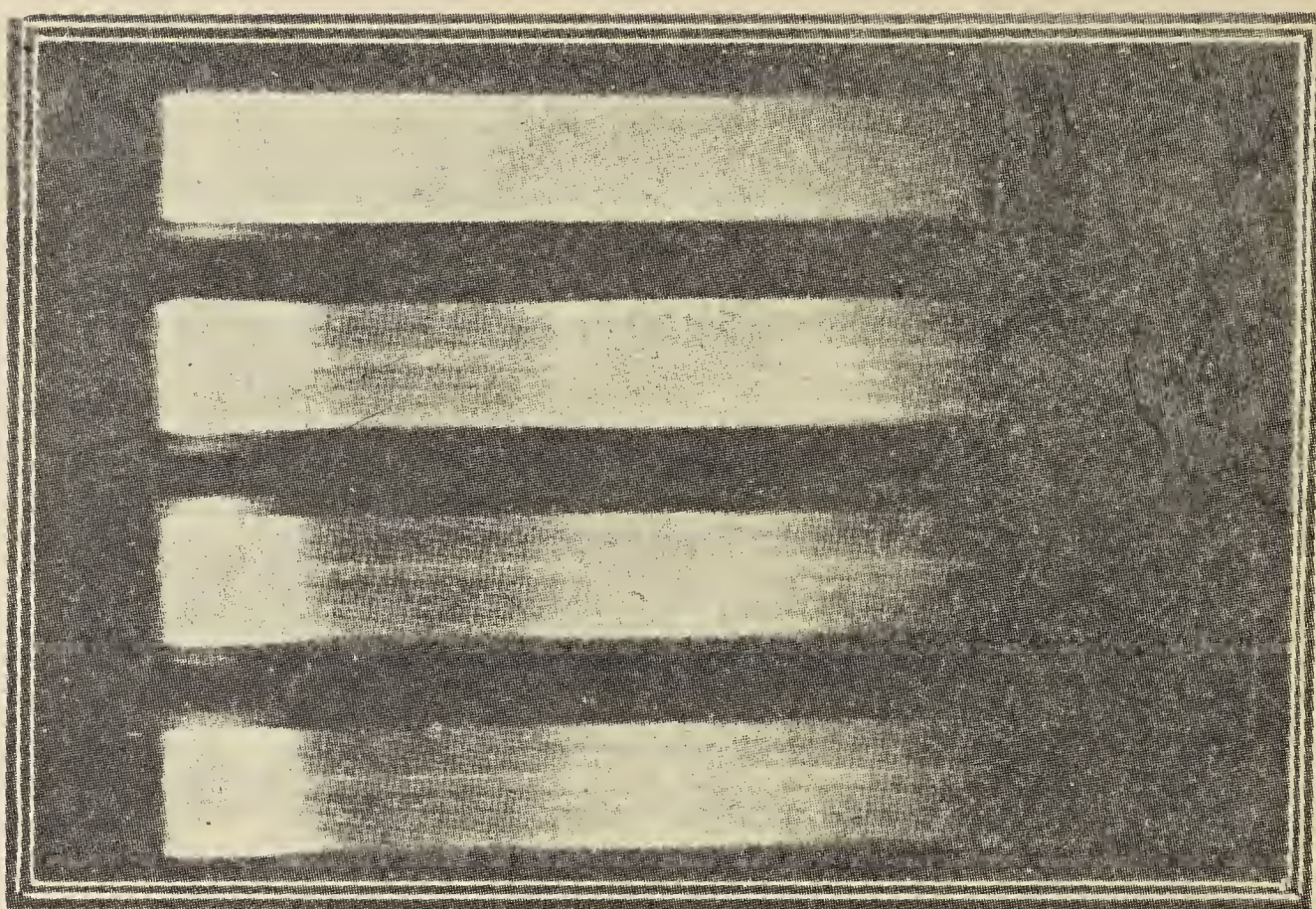


Figure 7. Flowers of the rose-crimson *Ipomea*.

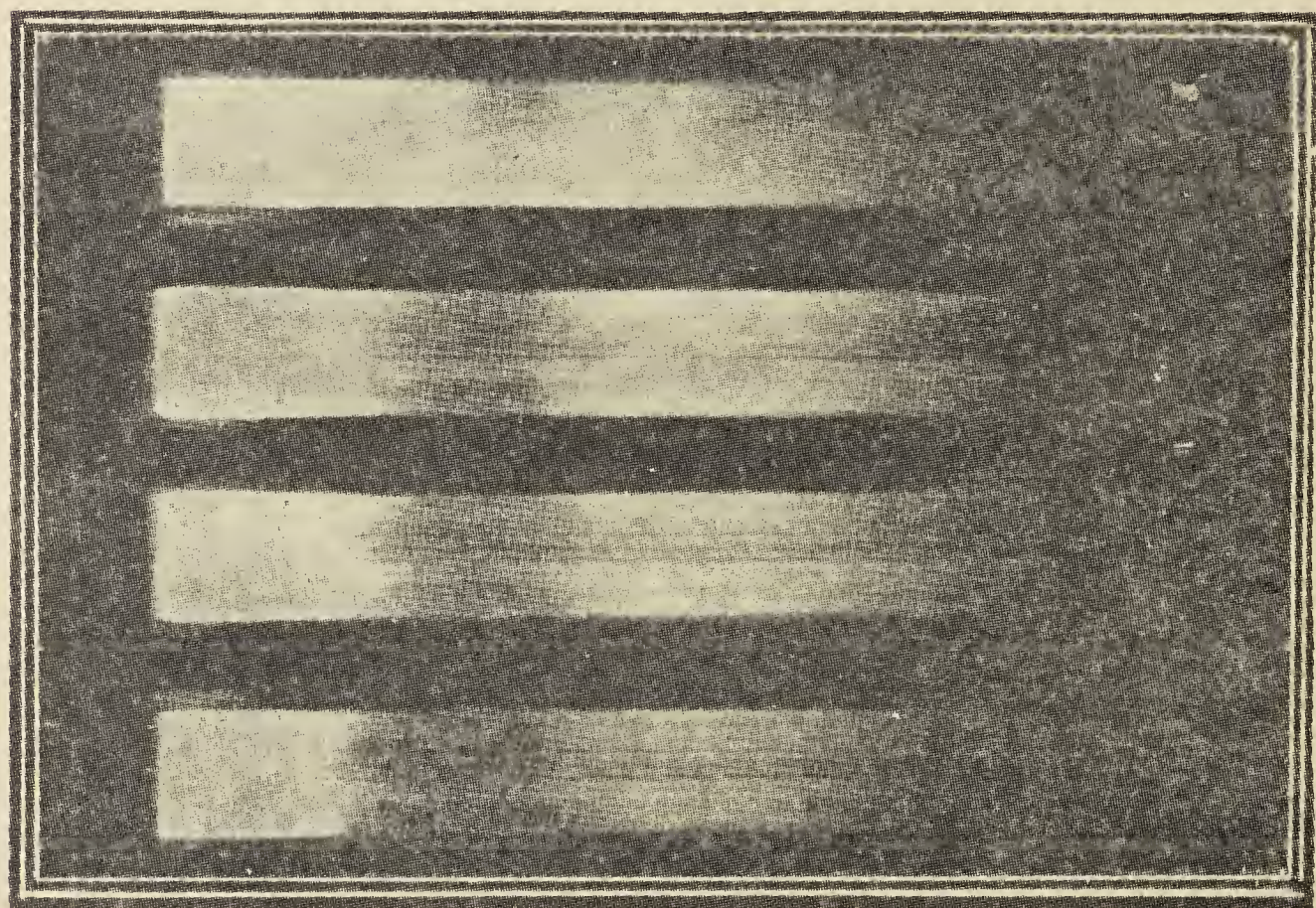


Figures 1 and 2. 1. Absorption spectrum of yellow flower (*Caesalpinia pulcherrima*) with comparison spectra 2. Absorption spectrum of orange-yellow lily with comparison spectra.

(1)



(2)



Figures 1 and 2. 1. Absorption spectra of petal of purple *Balsam* flower with comparison spectrum. 2. Absorption spectra of petal of crimson flower of *I pomea horsfalliae* with comparison spectrum.

for. But a noteworthy feature is that light of wavelengths less than $490\text{ m}\mu$ (in other words, the blue part of the spectrum) also makes an appearance in the transmission by the petals (*see* figure 2 in plate III of part IX reproduced with the ninth part of the memoir). But no indication of any admixture with blue appears in the colour of the petals. The observed orange-red hue of the petals is what we should expect on the basis of the transmission of the yellow, orange and red regions of the spectrum. The petals are vividly chromatic and present no suggestion of any unsaturation in their hue. We are thus led by the facts to conclude that the radiations appearing in the yellow, orange and red sectors of the spectrum mask the visual effect of the blue region transmitted by the petals of the pomegranate flower.

Figure 7 represents a flower and some buds of the creeper *Ipomea horsfalliae* which is remarkable for the bright colour as well as for the profusion of the flowers which it bears. (An excellent reproduction in colour of its foliage and flowers appears facing page 125 of Mr Cowen's book *Flowering Trees and Shrubs in India* which has been mentioned earlier). The flower has five thick ribs which hold together the thinner membranes between them which allow more light to come through. The light which penetrates the membranes shows a complete extinction of the green of the spectrum. But both the red and the orange as well as the blue-violet are transmitted freely as is manifest from the spectra reproduced as figure 2 in plate II. It is clear that the light appearing in the region of greater wavelengths suppresses the visual effects of the shorter wavelengths coming through the petals. Such masking or suppression of the visual effect of the blue and violet regions in the spectrum by those of the red, orange and yellow when the green has been excluded by absorption occurs with numerous other flowers. Indeed, we have already in the earlier parts of the memoir discussed in detail several cases of the kind in which this effect determines the observed colour of the flower.

Summary

The results emerging from the study of the individual cases have been brought together in this part of the memoir and illustrated by further examples. In particular, the special role in the physiology of vision played by the yellow region of the spectrum and the remarkable manner in which its presence or absence determines the character of the sensory impressions produced by polychromatic radiation are described. It also emerges that in certain circumstances, the sensory effect of the two parts of the spectrum on either side of the yellow may be masked or suppressed, one by the other, or *vice versa*.

Floral colours and the physiology of vision— Part XII. Some concluding remarks

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A logically sustainable foundation for physiological optics is provided by the two following propositions:

- A. The pure colours of the spectrum are the primary physiological sensations and these are as numerous as the number of distinguishable colours in the spectrum.
- B. The progression of colour visually perceived in the spectrum is consequential on the progressive increase in the energy of the light-quantum incident on and absorbed by the visual receptor.

These propositions may be considered as axiomatic. For, they only state in explicit language what we are entitled to assume to be true, viz., that the physical characteristics of light and our sensory perceptions of it are very simply related to each other. Indeed, Newton in the first part of his classic treatise on optics stated the first of our two propositions in perfectly clear language, while in a later part of the same treatise, he explained the colour-sequence observed in the spectrum as a consequence of the varying “size” of the corpuscles which he assumed light to consist of.

An extremely important characteristic of monochromatic light is the variation of its luminous efficiency as also of the threshold of colour discrimination over the range of the visible spectrum. In an earlier publication by the author (reference 1), the explanation of these features has been discussed in detail on the basis of the foregoing two propositions and it was shown that they are highly successful in accounting for the facts of observation. It is, therefore, unnecessary to traverse the same ground here. The present studies on the colour sensations excited by polychromatic radiations traverse a much wider field and it is therefore not surprising that many new results have emerged. But these do not conflict with or contradict the results of the earlier studies but on the other hand support and reinforce them. That the facts of polychromatic colour-perception can only be explained on the basis of the recognition of the pure colours of the spectrum as the primary physiological sensations is indeed evident from the results set forth in the

eleventh part of the present memoir. It is especially clear from the extraordinarily important role which, as we have seen, is played by the relatively narrow region of wavelengths between 566 and 589 m μ , in other words, by the yellow sector of the spectrum.

In this connection, we may usefully recall the observations on the functioning of the human retina described in the earlier publications of the author. These made use of a special technique in which an observer views extended source of white light through a suitably chosen colour-filter held in front of his eye and after a little while suddenly removes the filter. A colour-filter dyed with methyl-violet which absorbs the yellow rays of the spectrum gives by far the most striking effects. When such a filter is held in front of the eye and then quickly removed, a brilliantly-coloured image of the foveal region of the observer's own retina flashes into his field of view. Comparative studies thus made with various colour filters (reference 2) show that the yellow sector of the visible spectrum plays a highly important role in the physiology of vision, a result which, as we have seen, also emerges from the studies described in the present memoir.

It should be fairly obvious to a reader of this memoir that the observations on floral colours and their spectral composition described and summarised in it are basically in conflict with the ideas and beliefs regarding colour and colour-mixtures current at the present time. In a recent publication (reference 3), the present author has examined the so-called trichromatic hypothesis originally put forward by Thomas Young and shown that neither in its primitive form nor in the more sophisticated presentations of it given by Helmholtz and later writers does that hypothesis possess any logically sustainable foundation. That the trichromatic theory of vision has many adherents at the present time is due to the current belief that it is capable of giving a satisfactory description of the facts regarding polychromatic colour-perception. When that belief has been shown to be unfounded, a total rejection of the Young-Helmholtz theory becomes inevitable.

Summary

The results of the present studies on the visual perceptions of polychromatic radiation support the fundamental thesis that the primary physiological sensations are those excited by monochromatic light. The so-called trichromatic hypothesis and the theories of colour vision based on it are not logically sustainable. They are further contradicted by the facts of observation described in the present memoir.

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Fluctuations of luminosity in visual fields

SIR C V RAMAN

The phenomena briefly described and commented on in the present communication are obviously of fundamental interest and offer a promising field for further investigation. It appears desirable to mention the actual circumstances in which they first came under the author's notice.

The early hours of the morning in a darkened bed-room afford a convenient opportunity of observing how our visual perceptions of the brightness and colour of various objects are influenced by the strength of their illumination ranging from complete darkness before dawn to ordinary daylight levels after sunrise. Comfortably esconced in bed, the author watched the appearance of a smoothly distempered wall about three meters away from his eyes under these conditions. The light reaching the wall was that from the southern sky falling on it through two ventilators high up near the ceiling of the room. The illumination was sensibly uniform over the area under observation. But not until some time after sunrise when all the objects in the room exhibited their normal outlines and colours, did the wall present the appearance of a uniformly illuminated surface. At all earlier stages, it exhibited a fantastic play of moving light and shade, difficult to describe but which showed a progressive alteration in its character as the strength of the illumination increased from the zero level upwards. At the lowest levels of illumination, dark patches of extensive size appear to move over the wall, becoming visible and then disappearing. At somewhat higher levels of illumination, the darker and brighter areas are distinctly smaller and shift about in a random fashion. At still higher levels, the wall appears to be covered by innumerable scintillations, continually varying in their positions and degrees of brightness. In the final stages, the areas of fluctuating brightness appear to be quite small and contiguous to each other.

As the eyes of the observer had been rested in the dark for many hours before the effects described were noticed, it is evident that the phenomena reported are entirely characteristic of our visual perceptions and are not in the nature of any after-effects of earlier exposures of the eye to light. One may also rule out the possibility of ascribing them to retinal "light" of purely subjective origin. This is clear from the manner in which the effects observed change with the strength of the illumination.

Essentially similar phenomena can be observed and studied under controlled conditions in a darkened room, using artificial sources of light of which the

intensity can be varied over the necessary large range. For example, we may use an ordinary tungsten-filament lamp with a frosted bulb as the source of light. Enclosing this in a box covered with apertures of various sizes through which the light can emerge, the intensity of the light received on an observing screen can be varied. A white reflecting screen or else a translucent plastic screen can be employed; in the latter case, the light emerging through the screen is viewed.

The explanation of the effects that naturally suggests is one which makes use of the fundamental notions of the quantum theory. Before light can be perceived by an observer, the energy of the radiation falling on the retinae of his eyes has to be absorbed and passed on through the visual receptors and the optic nerves to the brain. Such absorption necessarily takes place in complete quanta, and we may reasonably assume that the visual sensations we experience would be determined, firstly by the number of radiation-quanta falling on the retina in each small interval of time; secondly, by the proportion of that number that is actually absorbed and thereby becomes available for perception, and thirdly by the extent of the region of the retina in which the visual receptors are located which actually take up a quantum of energy. The smaller the area of this region on the retina, the more highly localised would be the region on the screen on which the resulting illumination would manifest itself. Each of these factors would influence the results, and taken altogether they would determine the observed effects. The appearance of fluctuations of luminosity in the visual field may thus be regarded as a direct consequence of the energy of light consisting of discrete quanta. The weaker the illumination, the more conspicuously would the resulting fluctuations be expected to manifest themselves. The changing character of the observed fluctuations at different levels of illumination would be explicable as the result of the visual receptors which actually take up the energy not being the same both at the lower and at higher levels of illuminations and also being connected with the cerebral centres in a different manner in the two cases.

It can also be suggested with some confidence that the phenomena now under consideration stand in intimate relationship with the subject of the acuity of vision and its variations, and especially with the well-known influence on visual acuity of the strength of illumination. Indeed, observational trials show that the fall in visual acuity with diminishing brightness of illumination appears in the same range of illumination as that in which the fluctuations in the luminosity of a uniformly lighted screen are distinctly observable. We are therefore entitled to infer that our eyes fail to perceive the details of the object viewed by them at low illuminations for the same reason that a uniformly lighted screen at such illuminations exhibits purely subjective variations of its observable luminosity.

Finally, we may remark that the effects with which we are concerned in the present communication are conspicuous at levels of illuminations much higher than those approaching the lower limit of visibility, where the notions of the quantum theory have been utilized to explain various facts of observation. It may also be remarked in this connection that the fluctuations of luminosity with which

we are concerned here may be observed when the light sources are covered by various colour filters and the corresponding colours can actually be recognized on the observing screen. As is to be expected, the fluctuations of luminosity are most conspicuous with filters of low visual luminosity transmitting blue light and least conspicuous with the yellow filters which have a higher luminosity.

The visual synthesis of colour

SIR C V RAMAN

1. Introduction

Our visual organs possess in a high degree the faculty of distinguishing between the colours exhibited by the spectral components into which polychromatic radiation has been resolved by a dispersing apparatus such as a prism or a diffraction grating. On the other hand, without the aid of such apparatus, our eyes fail to recognise the presence of distinct spectral components in composite radiation. What they do perceive is the resultant sensation excited by it which is also (rather loosely) termed as the colour of the light. The number of such composite colours which can be distinguished from each other in appropriate circumstances is enormously larger than the number of monochromatic radiations which can be recognised as different in colour in a perfectly resolved spectrum. This is not surprising, since the nature of the polychromatic radiation, in other words, the distribution of energy in its spectrum admits of an infinite number of possible variations.

A knowledge of the relationship between the spectral nature of composite light and the character of the visual sensation which it excites is of great technical importance in various arts and industries. But it is no less important in relation to our understanding of the basic aspects of the physiology of vision. The only procedure for obtaining such knowledge which is not biased or invalidated by the prior acceptance of *ad hoc* hypotheses and can therefore be trusted to lead us to the real truth of the matter is the study of the relationship which actually exists between colour and spectral composition in a very large number of actual cases and the deduction from the results of such study of general principles which are found to be valid in all cases. These considerations led the present writer to undertake the systematic examination of floral colours in relation to their spectral composition. The results of the investigation of numerous individual cases were described and the inferences to which they pointed were set down in a recently published memoir by the author.¹ Since then, many more examples have been studied and satisfactory spectrograms illustrating the observed relationships in various cases have been recorded. The investigation has

1. "Floral Colours and the Physiology of Vision." Memoir No. 137 of the Raman Research Institute, *Proc. Indian Acad. Sci.* A58, 57, 1963.

also been extended to other classes of objects exhibiting colour, viz., gemstones (both natural and synthetic) and various technical products including especially dyed textiles. The results emerging from all these studies are in complete agreement with each other, as also with the conclusions arrived at in the memoir cited above. They make it evident that the geometric representations of the results of colour synthesis which have found favour for over a century, viz., the Maxwellian colour-triangle and the more recently adopted XYZ system, are based on a totally misconceived ideology and that the results indicated by these diagrammatic representations of colour are contradicted by the facts of observation.

2. The African violet and other flowers

The spectral composition of the colours of some hundreds of different floral species and varieties have been examined by the author. Amongst those more recently studied, three examples have been chosen as meriting special description in the columns of *Current Science*. The first example is that of the flowers of the plant known botanically as *Saintpaulia ionantha*, and more popularly as the African or Usambara violet. It is a small herbaceous perennial plant of great beauty which is almost stemless with a rosette of long stalked hairy leaves. The flowers are coloured deep purplish violet and resemble violets in shape though in size they are much larger (see figure 1). Throughout the year, the plant flowers freely. The second example belongs to the very interesting class of plants known as the Iris which bear curiously constructed flowers of attractive and gorgeous



Figure 1. Leaves and flowers of the African violet.

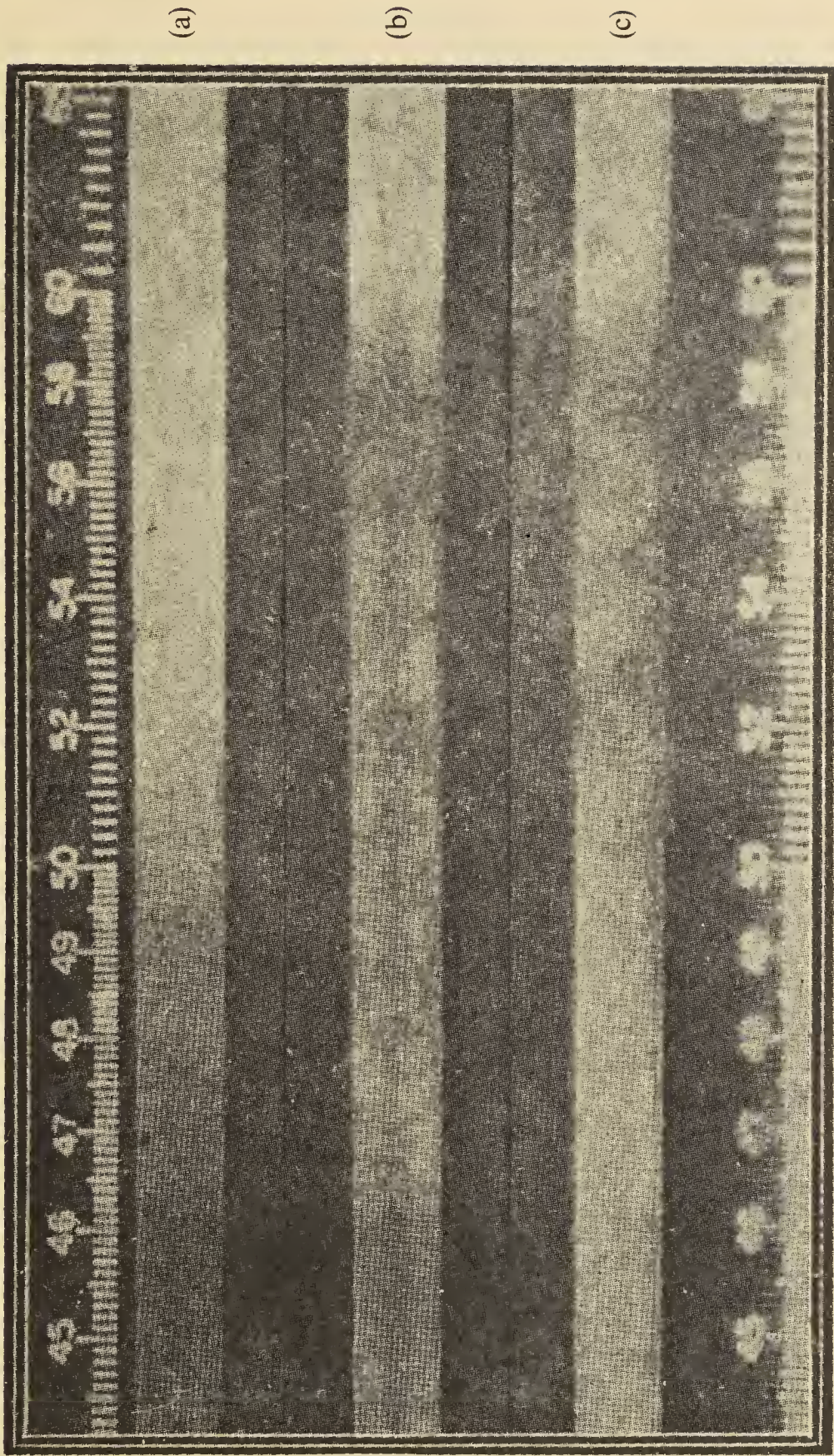


Figure 2. Spectrum of the African violet. (b) by transmission; (c) by reflection.



Figure 3. Petals of the Iris flower, spread flat.

colours. The particular plant whose flowers have been examined is *Iris germanica* which has sword-like leaves and bears flowers on erect stalks. They have a beautiful purplish-blue colour, a drawing of one such flower spread out flat on a sheet being reproduced as figure 3. The third example studied is a ground orchid which bears flowers on long spikes which may be 2 to 3 feet long. A group of such flowers appearing at the end of a stalk is illustrated in figure 5. The plant has been identified from the published descriptions and illustrations as the orchid *Spathoglottis plicata*. The most attractive of its varieties is one which bears flowers having a colour which may be described as a purplish-red. Spectrograms obtained with these three flowers are reproduced as figures 2, 4 and 6 respectively. We shall proceed to describe the features exhibited in these spectrograms and comment on their significance in relation to the theory of colour perception and the visual synthesis of colour, the latter being the special subject of the present communication.

3. The spectroscopic observations

The spectral composition of the colours of flowers may be studied either by transmission through their petals or by reflection at their surfaces. In the case of the African violet, the upper and lower surfaces of the petals present a slightly different appearance, the upper being of a deeper and more saturated violet hue. The colour as seen by reflection at the upper surface is likewise deeper and of a more saturated hue than that seen by transmission. The most striking feature observed in the spectrum of either the transmitted or the reflected light is an

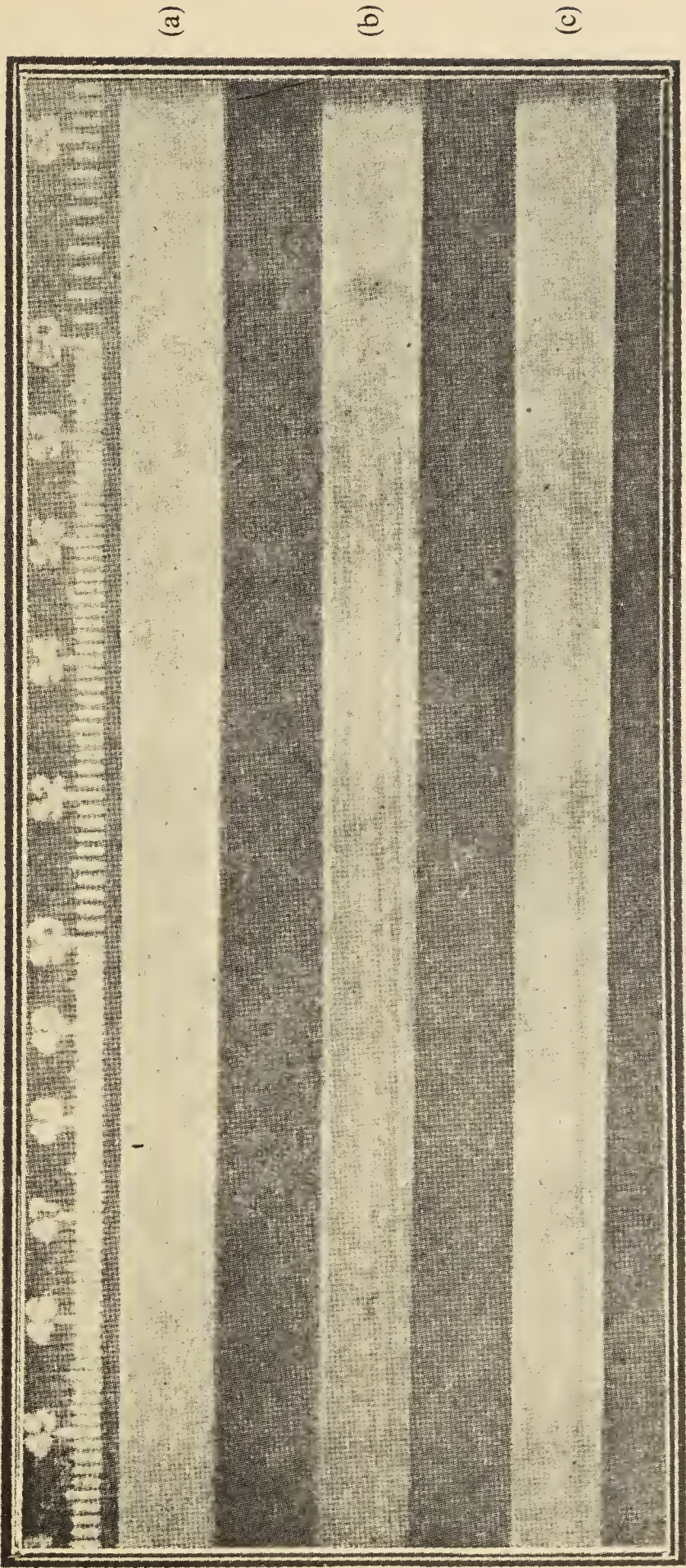


Figure 4. Spectrum of the Iris. (b) by transmission; (c) by reflection.



Figure 5. Bunch of flowers of the orchid.

intense absorption in the yellow region of the spectrum. This covers the region between 560 and 590 $m\mu$ and is very clearly exhibited in the two spectrograms reproduced as figure 2(b) and (c) respectively. Figure 2(a) is a comparison spectrum of the light source employed, viz., a tungsten-filament lamp. Remarkably enough, the red of the spectrum is conspicuous both in the transmitted and in the reflected light. It is evident, however, that considered in relation to the rest of the spectrum and especially the blue and violet, it has suffered a weakening. Further, it is noticed visually that in the spectrum of the reflected light, the red of the spectrum is split into two parts by a darker region located at 640 $m\mu$. The spectrum also reveals a weak absorption in the green located at about 530 $m\mu$. But these are relatively minor features. As is clear from the reproduced spectra, the major feature is the suppression of the relatively narrow yellow sector of the spectrum.

As stated earlier, the petals of the Iris exhibit a beautiful purplish-blue colour. The spectra of the light transmitted and reflected by its petals are reproduced in figure 4(b) and (c) respectively, figure 4(a) being the comparison spectrum of the light source. It will be noticed that the spectra exhibit an absorption in the yellow sector between 560 and 580 $m\mu$, but this is not so strong as in the case of the African violet.

The spectrum of the light transmitted by the petals of the orchid *Spathoglottis plicata* is reproduced in figure 6(b), alongside of the comparison spectrum of the light source, figure 6(a).

Two strong absorption bands are noticed, one between 580 and 590 $m\mu$ in the

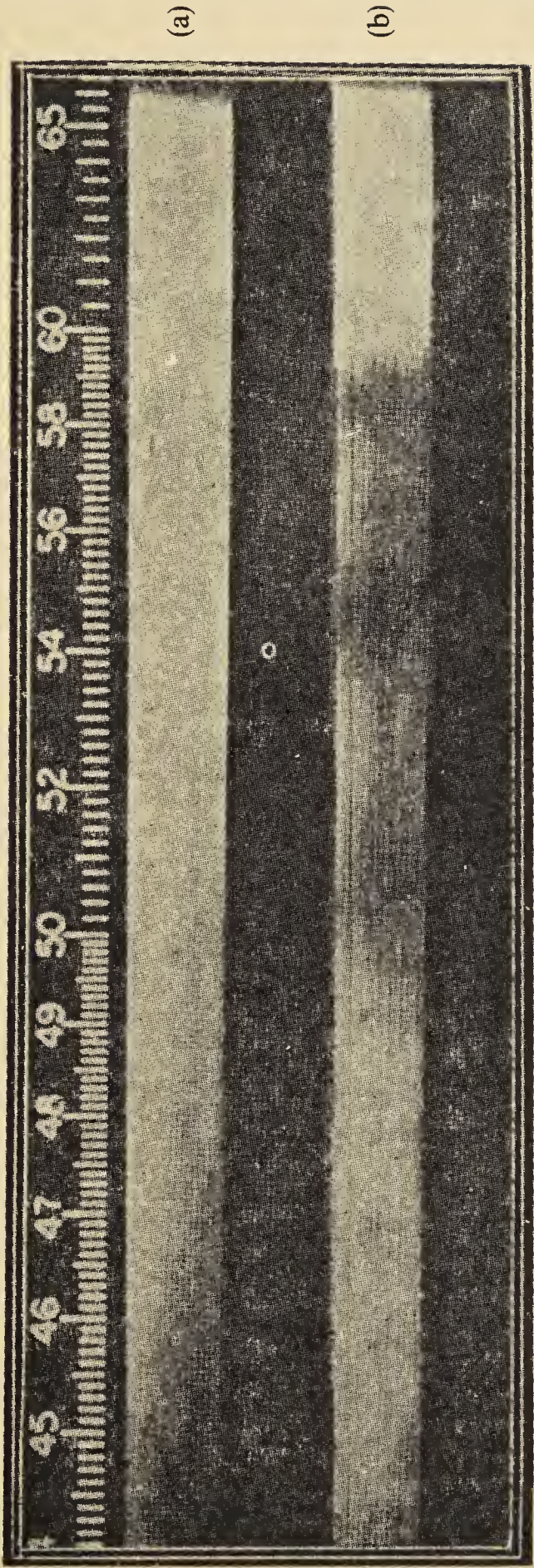


Figure 6. Transmission spectrum of the orchid with comparison spectrum.

yellow sector and another between 540 and 550 $m\mu$ in the greenish-yellow part of the spectrum. A third and much weaker absorption is also noticed at 510 $m\mu$, but the rest of the green between 510 and 540 $m\mu$ is transmitted freely. Neither the violet and blue sectors between 400 and 500 $m\mu$ nor the red sector show any noticeable weakening or extinction.

4. The significance of the results

We may sum up the foregoing by the statement that the absorption of the yellow is the major common feature in the spectra of the flowers in all the three cases, and that the large differences in their observed colours arise from certain relatively minor differences in the character of their spectra.

The highly important role played by the yellow region of the spectrum in determining the observed colour of composite light by reason of its presence or of its absence as the case may be, emerged very clearly from the studies described in the author's memoir on floral colours cited earlier. It was there shown that the removal of the yellow from the spectrum, other parts of the latter remaining the same, results in the observed sensation being the colour familiarly known as *purple*. Numerous illustrations of this fact were noted in the study of floral colours. The same result is demonstrated in a very striking fashion by technical products of various sorts, as for example, by silks which have been dyed a purple colour. In the author's collection of doctor's gowns acquired at various times, there are three examples of this, which may be referred to respectively as Calcutta-1922, Glasgow-1930 and Delhi-1964. The Calcutta gown is made entirely of purple silk. The Glasgow gown is of wool dyed scarlet, but it has purple silk facings and the hood is also lined with purple silk. The Delhi gown is of scarlet-coloured silk, but the cap is of purple velvet with edgings and an inside lining of purple silk. The three examples of purple silk exhibit three different shades of colour. But the spectral composition of the colour is essentially the same in all three cases, viz., a complete or nearly complete extinction of the yellow sector of the spectrum in the 560 to 590 $m\mu$ region, while the violet, blue, green and red sectors of the spectrum are present with their normal relative intensities as visually observed.

In the Maxwellian colour triangle, as also in the well-known XYZ representation of the results of colour synthesis, the purples appear on a straight line joining the two extremities of the spectrum, viz., red and violet. The purples appear in the diagram opposite to the bend in the curve representing the green part of the spectrum extending from 500 to 550 $m\mu$, the purple and the green being complementary colours. In other words, the diagram contemplates that the purple sensation results from the removal of the green from the spectrum. Actually, as we have seen, the purple sensation results from the yellow sector of the spectrum being removed, and it is experienced in a fully saturated form even

though the green part of the spectrum is present in full strength. Then, again, as has already been set out in the author's monograph, there are numerous flowers in which the green part of the spectrum is partly or wholly extinguished by absorption, while the rest of the spectrum is not weakened or absorbed. In all such cases, the colour exhibited is *not a purple*, but is a colour which ranges from a pale to a deep rose-red depending on the degree of completeness of the extinction of the green sector.

Thus, quite apart from any question of theory or logic, the actual facts of experience show that the ideology on which the Maxwellian colour-triangle and its more recent modifications are based is false and totally misconceived.

Stars, nebulae and the physiology of vision

SIR C V RAMAN

On any clear dark night we see the sky studded with stars, a few very bright ones, many more not so bright, and a much larger number of faint ones. They appear to us as points of light standing out of a dark background and possessing no visible extension. Numerous as the stars thus visible to the unaided eye are, their number is but a fraction of the multitude of stars revealed to our eyes when we are aided by such a modest item of equipment as a pair of binoculars. The stars made visible by using more powerful instrumental aid are even vastly more numerous. The reason is evident, viz., that the stars which appear faint are far more numerous than those which are bright and the same situation extends without limit to fainter and still fainter stars. This may be illustrated by reference to the actual numbers determined and listed by the painstaking labours of astronomers in their published star-catalogues. The so-called bright stars whose visual magnitude is less than 6.5 are about 9,000 in number, those of magnitude less than 8.5 number a quarter of a million and those of magnitude less than 10.5 more than a million. The scale of visual magnitudes adopted by astronomers is defined by the rule that the ratio of the brightnesses of two stars whose magnitudes differ by 5 is 100.

We may here ask ourselves two questions. Why are we unable with our unaided vision to perceive stars in the sky whose visual magnitude is more than, say six? Why does it become possible to observe stars of higher magnitudes with telescopic aid? Answers to both of these questions are given if it be assumed that for the eye to perceive a star, the light-flux reaching its image on the retina should exceed a specifiable minimum. This light-flux may be taken as proportional to the area which admits the light entering the eye. For the unaided eye, this would be the area of its pupil and when there is optical aid, this would be the area of the objective of the telescope. On this basis, an increase of the diameter of the objective by a factor of ten would enable stars to be perceived whose magnitude is larger by 5.

We shall now proceed to evaluate the light-flux reaching us from stars of various magnitudes. The basis of the calculation is the known value of the energy received by us from the Sun and the known value of the Sun's luminosity relative to the light received from the stars. "The total output of the Sun between $\lambda 5480 \text{ \AA}$ and $\lambda 5380 \text{ \AA}$ is $5.17 \times 10^{31} \text{ ergs sec}^{-1}$. The amount received per square cm at a distance from the Sun equal to the mean radius of the Earth's orbit or

1.496×10^{13} cm, is 1.838×10^4 ergs $\text{cm}^{-2} \text{sec}^{-1}$. The Sun's International photo-visual magnitude is -26.84 according to Kuiper. It therefore delivers to the Earth $10^{10.736}$ times as much light as a star of zero magnitude—in every wavelength if the star has exactly the same spectral type as the Sun. Hence the amount received per square cm per second per 100 \AA at $\lambda 5430 \text{ \AA}$ from a star of type dGo and of magnitude. 0^m .ooIPv is 3.37×10^{-7} ergs; and the logarithm of the energy received from any star of this spectral type is $7.53 - 4m_{vv}$." The above is quoted from the book on "The Outer Layers of a Star" by Woolley and Stubbs, Chapter XIII, page 274, where the corrections needed for stars of other spectral types are also listed.

In vision, we are chiefly concerned with the spectral region between 5000 and 6500 \AA , as the luminous efficiency of radiation becomes rather small outside those limits. It is therefore sufficient to consider the energy appearing between these limits in the spectrum of a star in seeking to explain its visibility. In the spectral energy curves for a perfect radiator at 5740°K . which is the effective solar temperature, the wavelengths 5000 and 6500 \AA are not far from the wavelength at which the radiation is a maximum. We shall therefore be justified in taking the flux of energy which determines the visibility of a star of the same spectral type as the Sun to be fifteen times the energy flux for a range of 100 \AA quoted above. This may conveniently be expressed in terms of the quantum of energy corresponding to the wavelength 5600 \AA which is that of maximum luminous efficiency. The number of light-quanta per second reaching the unaided eye from stars of various magnitudes has been thus calculated and shown in table 1, the area of the pupil of the eye being taken as 50 square.

We may now proceed to consider the significance of the figures listed in table 1 against the increasing orders of magnitude of the stars. If it be assumed that a single quantum of light is actually taken up by the visual receptors and passed on to the visual cortex could produce a detectable sensation, it is clearly necessary that the quanta should follow each other in rapid succession to enable the eye to perceive a star *steadily*. 30 quanta following each other in each second would probably suffice to produce a lasting impression. Actually, the table shows that a 6th magnitude star (which experience shows can just be perceived) has a light-flux

Table 1. Light-flux received by the eye

Magnitude of star	Quanta per second	Magnitude of star	Quanta per second
0^m	7,10,000	6^m	2,900
1^m	2,90,000	7^{th}	1,140
2^m	1,14,000	8^m	450
3^m	45,000	9^{th}	180
4^m	18,000	10^{th}	71
5^m	7,100	11^{th}	29

of 2,900 quanta per second, while stars of higher magnitude which have a smaller light-flux are not perceived at all. A reasonable explanation that can be offered for the facts is that the visual receptors take up or absorb only about 1% (averaged over the spectral range under consideration) of the light-quanta which reach them and transmit the impulses to the cerebral centres, while the rest go through unabsorbed to the pigment epithelium behind the retina. The number of quanta taken up and thus passed on would then just suffice in the case of a 6th magnitude star to enable us to see it steadily, while for stars of higher magnitude, it would be inadequate to produce such a result.

When we view the sky fixing our eyes on a particular star located on it, we have nevertheless no difficulty in recognising the presence of numerous other stars both far from and near to the one so regarded. The question then arises whether the brightness of any two stars as visually perceived in these circumstances depends to any noticeable extent on their positions relative to each other in the field of view and whether the visibility of any particular star depends markedly on its position in the field with respect to the point at which vision has been fixed. Both of these questions have an important bearing on the known variations in the anatomical structure of the retina as we pass from the fovea outwards. No answers can be given to these questions which are worthy of credence unless they are based on systematic observations and a careful comparison of our subjective impressions with the objective record furnished by photographic charts of the part of the sky under observation. If no effects of the kind indicated actually exist, it might reasonably be inferred that the visual process by which a point source of light is perceived does not vary sensibly in its nature over the area of the retina.

Other interesting questions arise which can only be answered by the results of specific investigations. It is familiar knowledge that when the night sky presents a background of continuous illumination, as for example, when the Moon is well above the horizon, the visibility of the fainter stars is seriously impaired. What is the precise origin of this effect, and how is the diminished visibility related quantitatively to the strength of the diffuse illumination of the sky? Then, again, is it possible to perceive quantum fluctuations in the visibility of faint stars? Here the difficulty presents itself of the fluctuations in brightness of stars due to the turbulence of the atmosphere which would also be present and interfere with the observations.

Having discussed the visibility of the stars of various magnitudes, we pass on to consider the highly interesting question of their colours. As seen by the unaided eye, a few of the very brightest stars show a hint of colour. But the vast majority of the stars appear to our unaided vision as mere specks of light of greater or less brightness and give no indication of the great differences in the spectral character of the light which they emit and the very large differences in the effective surface-temperatures inferred from these spectral characters and also from the luminosities as measured by photoelectric and photographic methods using colour filters to isolate different parts of the spectrum. The effective surface-temperatures range

from 25000° K. for stars of the spectral class, BO, 5520° K. for those of spectral class G5, to 2710° K. for the spectral class M5. These enormous differences show up very clearly when the luminosities of the stars are determined using colour filters as stated above; the colour-index of a star is the difference between its magnitudes in two colours. It is frequently given as the blue *minus* the yellow or visual (B–V) magnitude. This difference may be as much as two whole magnitudes for a star belonging to the spectral class M.

We may, therefore, well ask ourself the question why our unaided vision fails to reveal the great differences in colour which might have been expected in the circumstances stated above. Here, a significant remark may be made, viz., that the colours of the fainter stars become distinctly more manifest when the stars are viewed through a telescope with an adequate aperture. Colour-differences between the two components of double stars also become noticeable with such aid and are indeed to be found indicated in the published catalogues of various observers. It is obvious from this that the magnitude of the light-flux reaching the retina from a star not only determines the visibility of the star and its brightness or luminosity, but also plays a highly important role in the perception of colour. We are indeed led to the inference that as the number of light-quanta received per second by the eye from a light-source progressively increases, the sensations of luminosity and of colour develop *pari passu* and become more pronounced. When the light-flux reaching the eye is small, we perceive a dim and characterless luminosity. As the light-flux increases, our perceptions develop into a bright and colourful sensation.

A great many years ago, the author visited the Mount Wilson Observatory near Pasadena and enjoyed the privilege of sitting at the eyepiece end of the 60-inch reflector one night and of the 100-inch reflector another night. Amongst the objects chosen for viewing through these telescopes were the famous Ring nebula in Lyra and the Great nebula in Orion well-known to all amateur astronomers. The writer was familiar with the appearance of these objects as seen through a 7-inch refractor available to him at Calcutta and was enormously impressed by what he saw of them through the great telescopes at Mount Wilson. The Ring nebula in Lyra exhibited flaming colours changing progressively from the external edge of the ring to its inner margin. The Great nebula in Orion which in smaller instruments appears as a shapeless patch of light without noticeable colour is seen with the sixty-inch as a blazing area of variegated colour determined by the light-emission of the gases of which it is composed. The impression left on the writer by these experiences was so vivid that it was recalled and a special reference made to it in a broadcast on "The Stellar Universe" given several years afterwards at Madras. This appears in a printed collection of the author's radio-talks on various aspects of science published by the Philosophical Library, Inc., of New York in the year 1951.

When we look at a star directly or when we view a star or a nebula through the eyepiece of a telescope, we make use of the region of the fovea in the retina. It

follows that everything that has been stated above regarding the perception of light and colour refers to the functioning of our eyes in photopic vision, so termed by writers on physiological optics. It is a fact that our eyes are capable of functioning in very dim light and enable us, for example, to find our way through the countryside on a dark night when the landscape is lit only by starlight. This is scotopic or dim-light vision. But if, in the same circumstances, we look up and view a star which is a concentrated point-source of light, it is photopic and not scotopic vision that is functioning. That we are unable without optical aid to see stars of magnitude higher than six or to perceive the colour in any except the very brightest of stars are therefore characteristic features of photopic vision.

The real distinctions between photopic and scotopic vision are that scotopic vision does not function except when the eyes have been prepared for it by having been rested in the dark for an adequate period, and scotopic vision does not at all function in red light even after such a period of rest. It is often stated and generally believed that scotopic vision is achromatic while photopic vision alone is associated with the possibility of observing and recognising colour. Since, as we have seen, even in photopic vision, colour sensations become enfeebled at low levels of luminosity, likewise it is to be expected that they would be extremely weak at the very low levels of illumination at which scotopic vision functions. But that they are not wholly absent in scotopic vision even at such levels has already been noticed and remarked upon by the writer in an earlier publication (*Memoir No. 125 of the Raman Research Institute*, Vol. VIII, 1960, page 11).

The new physiology of vision—Chapter I. Introductory

SIR C V RAMAN

Received August 17, 1964

The faculty of vision plays an immensely important role in human life and activity. There are three different aspects of that faculty, viz., the perception of form and space, the perception of luminosity and the perception of colour. Each of these categories of perception is operative over a wide range of variation of the effects perceived. Very remarkable, also, is the degree of precision and capacity for discrimination exhibited in each case. A fuller understanding of these features of our visual perceptions is obviously of the highest interest and importance.

The beliefs currently entertained regarding the matters referred to above have been largely inherited from the era of scientific advance when it was thought that the wave-theory of light was the proper foundation for an understanding of the phenomena of vision. To find a way out of the difficulties then arising, certain hypotheses and assumptions were introduced and adopted as articles of faith, thereby inhibiting an unbiased study of the facts which would have revealed their inadmissibility. Physiological optics thus became a species of make-believe, instead of real knowledge based on reason and experiment.

On the 2nd October 1959, the author gave at his Institute in Bangalore a lecture on “Light, Colour and Vision” which was an exposition of the outstanding features in the functioning of the visual organs of man. The lecture as actually delivered traversed only familiar ground, but the study of the subject undertaken at the time made it evident that great lacunae existed in our understanding of the facts of visual optics. The author was thereby encouraged to enter the field with a view to develop the subject on new lines.

The first steps in the direction indicated were taken in the author’s address to the Annual Meeting of the Indian Academy of Sciences in December 1959, which was published in *Current Science* for January 1960. The title of the address was “The Sensations of Colour and the Nature of the Visual Mechanism” and it sought to interpret the known facts of colour perception and colour discrimination on the basis of a new concept of the functioning of the human retina, viz., that it receives the energy quanta of the incident light and transforms them into electrical impulses which travel along the optic pathways and reach the cerebral centres.

Soon afterwards, the author devised a simple but highly effective method by which an observer can view his own retina in the act of functioning, in other words, perceive the response of the retina when light of any chosen spectral composition is incident on it. The method reveals that the foveal region of the retina differs greatly from the areas surrounding it in respect of the sensitivity to different parts of the visible spectrum.

In Memoir No. 125 of the Raman Research Institute entitled "The Perception of Light and Colour and the Physiology of Vision" published in December 1960, this method of studying the retina was described in detail and its results were illustrated by a few pictures of the retina in colour as thus observed. It was shown that by using colour filters which isolate particular regions of the spectrum for illuminating the retina, the method enables the spectroscopic behaviour of the absorbing pigments present in the retina to be determined and the manner in which they are distributed over its area to be ascertained.

The use of polarised light in conjunction with colour filters and the same technique enabled further progress to be made. It was shown that the absorbing material present in the retina which is effective in the blue region of the spectrum and enables it to be perceived is a carotenoid pigment having elongated molecules. In the foveal region of the retina, these molecules set themselves radially along the nerve fibres in that region. The well-known fact that the unaided eye can detect polarised light was thus shown to be a consequence of the molecular form and absorptive properties of the visual pigment which is effective in the blue region of the spectrum. Memoir No. 133 of the Raman Research Institute entitled "The Role of the Retina in Vision" published in August 1962 discusses these findings and includes more pictures of the retina in colour.

Early in the year 1963, the author commenced a systematic study of the immense array of material available for the study of colour in the shape of the flowers and foliage of the plant world. The aim was to determine by factual observations the relation which actually exists between the perceived colour and the spectral composition of the light reflected by or transmitted through the petals of flowers or the leaves of plants. Quite simple methods, viz., visual observation of the light through a pocket spectroscope provided with a wavelength scale enabled numerous samples to be quickly examined. The results of such observation were checked and confirmed by photographic registration of the spectra and a critical study of the record.

The results of the first few months of work on these lines were described and illustrated in Memoir No. 137 of the Raman Research Institute entitled "Floral Colours and The Physiology of Vision" which was published in August 1963. The results were extremely striking and they led to some significant conclusions regarding the colour sensations excited by polychromatic radiation. Later work with more material confirmed the results and conclusions set out in the memoir. Studies of a similar nature were also undertaken with natural and synthetic gemstones, textiles and technical products of various sorts exhibiting colour. The

results in every case supported the conclusions reached by the study of floral colours.

The outcome of the investigations was to establish the fundamental thesis that the primary physiological sensations are those excited by monochromatic radiation and to show that the sensations excited by polychromatic-radiation are not determinable by simple additive laws. The so-called trichromatic hypothesis and the ideas regarding colour synthesis based on it were found to be definitely contradicted by various facts of observation. One of the most striking facts emerging from the study is the extraordinarily important role played in colour synthesis by the relatively narrow region of wavelengths comprised in the yellow sector of the spectrum. Its presence or absence makes all the difference in the perceived colour of polychromatic radiation.

Under the title "Fluctuations of Luminosity in Visual Fields", the author described in the issue of *Current Science* dated the 5th of February 1964, a phenomenon of extraordinary interest discovered by him. Detailed studies subsequently made confirmed the explanation of it suggested in that preliminary communication. Briefly stated, the substance of the discovery was that a uniformly illuminated screen which diffuses the light falling on it exhibits localised fluctuations of luminosity over its entire area when viewed at some distance from it. The magnitude and character of the observed fluctuations are found to depend on the strength and spectral character of the illumination and especially also on the distance from which the screen is viewed.

It has been shown that these effects arise by reason of the corpuscular nature and behaviour of light. It is significant that they are observed over a wide range of illumination of the screen, which may be far above the absolute threshold at which the eye ceases to perceive light. Further studies have established that these fluctuations of luminosity stand in the closest relationship to the subject of visual acuity and that they explain the well-known dependence of the visibility of the details of an object on the strength of its illumination and the distance of the object from the observer. Indeed, the variations in the visibility of detail are found to be direct consequences of the local fluctuations of luminosity in the field in which the object is located.

In an article published in the issue of *Current Science* dated the 20th of May 1964 under the title "Stars, Nebulae and the Physiology of Vision," the author discussed the explanation of various familiar facts of experience regarding the objects appearing in the night-sky and our ability to perceive them and observe their characteristics. The article sought to find answers to various questions arising in that connection and especially the following. Why are we unable with our unaided vision to perceive stars fainter than the sixth magnitude? Why do the great majority of stars appear to us merely as specks of light without any hint of colour? Why do gaseous nebulae appear as mere patches of light in small telescopes while as seen through giant telescopes they appear as blazing masses of colour? It was shown in the article that highly significant conclusions regarding

the functioning of the visual organs emerge when these questions are examined in the light of the available data regarding the luminosities and spectral characters of the stars and the nebulae.

The foregoing is intended to convey some idea of the vistas of research in the physiology of vision which have been opened by the work of the author since October 1959 when his active interest in this field had its commencement. The account given above does not however attempt to state or even to summarise the results of that work. That is reserved for the succeeding chapters of this work.

The new physiology of vision—Chapter II. Visual sensations and the nature of light

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The special organs of sense are the gateways through which a knowledge of external circumstances and events finds its way into the domain of human consciousness. Such knowledge is, of course, a prime requisite for the work-a-day activities of the individual. There is another role which the sense-organs play which is also of high significance, viz., the special contributions they make to aesthetic values in human life. We may mention here music as perceived through the organs of hearing, perfumes through the sense of smell, and colour through the organs of vision. The study of these special aspects of perception naturally takes a very prominent place in the physiology of the respective sense-organs. It is significant that all the three faculties of perception exhibit certain common features, viz., their ability to function over a wide range of intensities of the external stimuli and the capacity, in appropriate circumstances, to notice them even when they are excessively feeble. We may also mention the rapidity with which the sense-organs function and the power which they possess of recognising even subtle differences in the characters of the exciting stimulus. All these features enhance the usefulness of the sense-organs in human life and activity.

The position of exceptional importance which vision takes amongst the faculties of perception is attributable to the special properties of the physical agency, viz., light, which our eyes make use of and which enables them to function. There are obvious relationships between these properties and the services which the faculty of vision can render. For example, light can travel swiftly through vast distances in space and still reach us and not disappear on the way. We are thereby enabled with our unaided vision, to perceive very distant objects, even those lying outside our own galactic universe, as for example, the Great Nebula in Andromeda. The rectilinear propagation of light in space is evidently also what makes it possible for us to locate various near objects around us. The differences in the spectral character of the light which reaches us, either from the original sources or from the objects which reflect, scatter or diffuse the light falling on them is likewise the basis on which rests the special faculty of colour perception. From all that has been said it follows that the physiology of vision is greatly concerned with the nature and properties of light, and unless

these are known and correctly understood, those pursuing the subject would be wandering about on false trails.

Light plays a dual role: At the end of the nineteenth century, the nature of light was regarded as an issue which had been settled once for all. The view adopted was that light is wave-motion which travels in free space with a velocity approaching 3,00,000 km per second. The electric and magnetic forces constituting the disturbance are mutually perpendicular and appear in a plane transverse to the direction of propagation of the waves. Monochromatic light is in the wave-theory characterised by a definite wavelength in vacuum and a correspondingly high but definite frequency of variation of the electric and magnetic forces. In view of what has been said above, one need not be surprised that the great leaders of scientific thought in the nineteenth century who were principally responsible for advancing and establishing the wave-theory of light also sought to interpret our visual perceptions on the same basis. They could not have foreseen that all such attempts were foredoomed to failure.

As is well known, a revolutionary change in our ideas regarding the nature of light was brought by the work of Albert Einstein in the early years of the twentieth century. Einstein revived the idea favoured by Newton in an earlier epoch of science, viz., that light is corpuscular in nature, but he put it forward in a modified form having both substance and definiteness. The light-corpuscles of Einstein represent specific amounts of energy in the radiation field, the quantum of energy being the smallest for light appearing at the red end of the spectrum and increasing continually as we proceed towards its violet end, being in fact proportional to the light-frequency. The support forthcoming for these concepts from many different directions has been so overwhelming that Einstein's idea are now a well-established part of scientific knowledge.

The corpuscular and wave-theoretical descriptions of light seem at first to be mutually contradictory. But as they are both supported by great arrays of factual evidence, a way of reconciling them has necessarily to be found. Such reconciliation becomes easiest if it be assumed that the two concepts are valid in completely different and mutually exclusive fields of experience. Wave-optics successfully describes the propagation of light in free space, its reflection and refraction at the boundaries between the two media, and the special effects known as interference and diffraction which are characteristic of wave-motion and which arise from the superposition of wave-disturbances from the same original source. The corpuscular concept, on the other hand, is essential for the consideration of all phenomena in which there is a transference of the energy of radiation to or from material bodies. The emission and absorption of light are examples of such phenomena, and they can be successfully described and explained only on that basis.

The corpuscular concept of light involves a further and quite fundamental change in our modes of scientific thinking. This also we owe to Einstein. The

emission or absorption of light by an atom or molecule in the corpuscular concept is not a continuous process but an individual event, and whether this occurs or not is a matter of chance. All that we can specify about it is the probability of its occurring and hence the observable phenomena arising from such events can only be described in statistical terms.

What has been stated above is of the utmost significance in relation to vision. The dioptrics of the eye and the formation of focused images of external objects on the retina clearly fall within the scope of wave-optics. But wave-optics is irrelevant in all considerations regarding the actual perception of light. Interactions of some kind between the incident light and the material present in the visual receptors are clearly needed for such perception to be possible. It follows that all aspects of vision, including the perception of space and form, the perception of luminosity and the perception of colour, can only be understood in terms of the corpuscular concept of the nature of light.

It needs here to be stated and emphasised that the quantum of energy which a corpuscle of light represents is an exceedingly small quantity by all ordinary standards. For example, for light of the wavelength $555\text{ m}\mu$ which lies in the green part of the spectrum, it is 3.566×10^{-12} of an erg. For longer and shorter wavelengths, the quantum is respectively smaller and larger, being in an inverse proportion to the wavelength. From these figures, and the known mechanical equivalent of light energy, a simple calculation enables us to find the number of light-quanta falling per second on unit area of an illuminated screen. Taking the strength of the illumination to be one metre-candle, in other words, one lumen per square metre, and that one lumen of illumination with light wavelength $555\text{ m}\mu$ is equivalent to 0.00154 watts of energy, the quantum of light energy of that wavelength comes out 3.566×10^{-19} watt-seconds. Hence, the screen would receive per second 4.3×10^{15} quanta per second per square metre of its area. This is an enormously large number.

In the following chapter we shall survey broadly the consequences which follow from a recognition of the corpuscular nature of light and discuss the role that it plays in our visual perceptions. In doing so, we shall not hesitate to draw the various inferences which follow as logical consequences of that concept, taken either by itself or taken in conjunction with certain well-established results of experiment.

The new physiology of vision—Chapter III. Corpuscles of light and the perception of luminosity

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In a communication published under the title “Fluctuations of Luminosity in Visual Fields” in the issue of *Current Science* on the 5th of February, 1964, a phenomenon discovered by the author was described, the general features of which indicated it to be a consequence of the corpuscular nature of light. The circumstances in which the phenomenon was observed and the nature of the effects seen were as follows. The observer views a uniformly illuminated surface situated at a sufficient distance from himself; it is noticed that its luminosity does not appear uniform or static, but exhibits fluctuations over its entire area. The nature and magnitude of the observed effects depend greatly on the strength of the illumination. A particularly noteworthy feature is that the fluctuations continue to be conspicuously noticeable even when the illumination of the screen is thousands of times more powerful than the absolute threshold at which the sensation of light itself vanishes.

The earliest observations of the phenomenon were made without any special arrangements. The illuminated surface was that of a wall in a darkened room on which the light of the sky entering through a ventilator near the roof was incident. The wall was itself distempered with a pale green wash and this greatly reduced the intensity of the light diffused by its surface. The observations were made in the early hours of the morning soon after dawn, so that the effect of the gradually increasing strength of illumination could be very conveniently followed, the observer being at a fixed distance from the wall. Subsequent observations under controlled conditions in a laboratory revealed the influence of varying the distance of the observer from the screen, as well as the highly important role played by the spectral character of the light in the observed phenomena. It was discovered that the effects were most conspicuous when the screen was illuminated with monochromatic light; the effects, though observable with light of all wavelengths, differed greatly in the measure of their conspicuousness for different parts of the spectrum.

Observations with monochromatic light: Definitive studies of the phenomenon were made in a fairly large laboratory room. This was ten metres square and

could be completely darkened. The observations were made using as the screen a plastic sheet which was perfectly white and $150\text{ cm} \times 100\text{ cm}$ in area. This was fixed vertically on a stand so that the distance of the screen from the source of light as well as the distance of the observer from the screen could be independently varied. The surface of the screen had a smooth polish, so much so that the image of the source of light reflected by it was seen sharply defined; but setting the screen suitably with reference to the position of the source and the observer, the reflection could be put out of sight, and only the light diffused by the material of the screen was visible. The screen was uniform and completely free from blemishes, so much so that its diffusing power showed no detectable variations over its entire area.

Monochromatic illumination of the screen could readily be achieved by using a sodium vapour lamp of modest size. This was enclosed in a box provided with an adequately large opening on one side and this was covered over by a diffusing screen of ground glass. The illumination of the distant screen could be varied over a wide range of values by covering the aperture through which the light issued with an iris diaphragm of which the opening could be varied from 10 cm diameter down to a mm, thereby enabling the illumination of the screen to be reduced by a ratio of 10000:1. As the distance of the screen from the source could be diminished from nearly ten metres down to about 10 cm, its illumination could be further altered over a ratio of about 10000:1. Thus, the intensity of the light falling on the screen could be varied from the maximum available in the immediate neighbourhood of the source to a value smaller than that maximum by a factor of about 10^{-8} . The strength of the illumination in the immediate neighbourhood of the aperture from which the light issued could be read with a light meter and was found (with the particular lamp under use) to be fifty foot-candles. When the diaphragm of the iris is closed down to the smallest value and the screen is at the maximum distance from the source, its illumination was found to be unobservable. Thus, the arrangements permit of the screen being viewed under a very wide range of intensities of illumination.

For obtaining monochromatic illumination other than that which could be provided by a sodium-vapour lamp, the most suitable arrangement was found to be the use of a mercury-vapour arc of the high pressure type enclosed in a quartz tube and to focus the image of the arc lamp upon the entrance slit of a double monochromator. An instrument of this kind obtained some years ago from Messrs Kipp and Zonen in Holland was available and was found to be well suited for the purpose. By adjusting the position of the central slit within the instrument, the radiation of any of the chief mercury-arc lines ($\lambda 4046, 4358, 4916, 5461, 5770\text{--}5790$ and 6150) could be effectively isolated from the rest of the spectrum and used to illuminate the distant screen. By varying the width of the slit through which the light finds entry into the monochromator, as well as of the slit

through which it finally emerges, the intensity of the issuing beam could be increased in a very considerable ratio without any noticeable loss either of the monochromatism of the emerging light or of the uniformity of illumination of the screen. With the arrangements indicated, the intensity of the emerging light is high in the immediate vicinity of the exit slit and can easily be read with a light-meter: it falls off rapidly in a calculable ratio as we move away from the slit.

Factors influencing the observed effects: As has already been indicated, three factors influence the nature of the observed phenomena. *Firstly*, the strength of the illumination of the screen; *secondly*, the distance of the observer from the screen; and *thirdly*, the spectral character of the illumination. With suitable arrangements, the effect of varying each of these factors could be separately studied. Before describing the observed results, a few remarks of a preliminary nature may be usefully made. It is desirable, though not absolutely essential, to make the observations in a room which has been completely darkened. The need for such darkening is obvious when we wish to make the observations at the lowest levels of illumination of the screen. But, even otherwise, it is desirable that the eyes of the observer are not distracted by light reaching them from other sources than the screen under observation. Especially if such sources are much brighter than the screen itself would be distracting effect be serious. For the same reason also, it is desirable that the observer should not proceed to view the screen immediately after entering the darkened room from a brightly illuminated exterior, but should allow a sufficient time for the visual after-images produced by exposure to strong light to disappear completely. The interval thus allowed would also serve for the adaptation of his vision to the level of illumination of the screen actually under study: the time-interval needed for such adaptation would be a few minutes if the level is high and would be much longer if the level is very low.

A further remark is here needed regarding the characteristics of vision of the observer. It is necessary, of course, that the screen should be seen distinctly by the observer from the position actually taken up by him. If his vision is good for both of his eyes for all distances, no further comment need be made. It is often the case, however, that vision of one eye is much better than that of the other; the observations can then be made with both eyes open, for the phenomena are effectively those seen by the eye of which the vision is good. If the vision of both eyes is equally good, it is found that the fluctuations are better seen when one eye or the other eye is covered up than with both eyes open. This is a clear indication that the fluctuations as seen by the two eyes are independent of each other and the binocular superposition tends to make them less conspicuous than otherwise. If both of the eyes are optically defective, it is necessary to wear correcting glasses. But this is not needful for observations made with screens held at a sufficient distance, if at least one eye of the observer has good vision for distant objects.

Effect of varying the luminosity: As has already been indicated, the strength of the illumination of the screen may be varied by one or another of two methods or by both together; firstly by altering the luminous flux issuing from the light source and secondly by varying the distance of the screen from the source. The former method has the advantage that the observer can remain at a fixed distance from the screen, and hence the effect of varying such distance does not arise. The change in the strength of the illumination can be effected in a quantitative fashion using the sodium-vapour lamp and varying the aperture of the iris diaphragm as already described. Using this technique, it is found that the fluctuations of luminosity of the screen are discernible over a great range of strength of its illumination. But the observable characters of the fluctuations differ greatly at different levels of illumination. The differences observed are of three kinds: firstly in respect of the degree of contrast observable as between the darker and brighter areas in the fluctuating illumination; secondly, in respect of the rapidity with which the changes occur; and thirdly, in respect of the sizes of the areas of brightness and darkness seen on the screen. We may describe the differences which are observed succinctly as follows. In the higher ranges of illumination, the contrasts between the areas of darkness and brightness are less, the areas themselves are distinctly smaller, and the changes with time are more rapid. At the lower levels of illumination, the contrasts are more striking, the areas are larger and the changes with time are slower. These differences in the characters of the fluctuations increase progressively with the decreasing strength of illumination.

Effect of varying the observer's position: When the observer alters his location and approaches an illuminated screen, the flux of illumination from any given area of the screen which finds entry into the pupils of his eyes increases in the inverse proportion of the square of his distance from the screen: but the image of that area formed on the retinae of his eyes increases in size in the same proportion, and hence it is not to be expected that the luminosity of the screen as actually perceived would alter sensibly. Actually, it is found that the fluctuating pattern of varying intensities visible on the screen progressively increases in the absolute scale of size of its details as the observer moves away from the screen; *per contra*, the details seen in the pattern visibly contract as he moves towards the screen. But other features of the pattern, viz., the contrasts between light and shade, and the rapidity of the fluctuations do not seem to alter. In the higher ranges of illumination of the screen, however, the patterns of fluctuation themselves are on a small scale and also change rapidly with time. Hence, it becomes more and more difficult to recognise the existence of the fluctuations when the observer approaches too closely to the screen under observation. For these reasons, it is desirable that he takes his stand at a reasonable distance from it, say, a metre or two from the screen. When, however, the illumination is very low, he can

approach much closer and still have no difficulty in recognising the varying patterns of light and shade moving over the screen.

Influence of the spectral composition: As is well known, the intrinsic luminosity of the visible spectrum varies greatly over the range of wavelengths included in it as we pass from one end of the spectrum to the other. The absolute level of illumination and the particular region of the retina made use of for the observations are also known to influence the form of the spectral luminosity curve. In these circumstances, it is only to be expected that the character of the fluctuations of luminosity visible on an illuminated screen would depend greatly on the position in the spectrum of the light employed for the observations. The light of the sodium-vapour lamp is not far in its position from the point of maximum luminosity in the spectrum at high levels of illumination. Since the fluctuations of luminosity are conspicuous with sodium light over a great range of intensities of illumination, one may reasonably expect that monochromatic light from the parts of the spectrum of which the intrinsic brightness is lower should exhibit the phenomena even more conspicuously. This is indeed found to be the case. As we move from the yellow into the red, and also as we move from the yellow into the green and then into the blue and the violet the effects become more strikingly visible. Indeed, the fluctuations of luminosity on a screen illuminated by the $\lambda 4358$ radiations of the mercury lamp are conspicuous even at high levels of illumination; indeed more so, than could have been anticipated on the basis of the low intrinsic luminosity of the $\lambda 4358$ radiation as compared with the 5896 light of the sodium lamp.

The origin of the fluctuations: The energy carried by an individual corpuscle of light is an exceedingly small quantity, and the number of corpuscles corresponding to even a moderate light-flux incident on a screen is enormously large. As has already been noted in the preceding chapter, a lumen of illumination of wavelength $555\text{ m}\mu$ falling on an area of one square metre is equivalent to the incidence on it of 4.3×10^{15} quanta per second of time. This number being enormous, it might seem incredible that observations of an illuminated screen should enable us to perceive any noticeable fluctuations in brightness. The paradox is resolved when we consider the situation more closely. We have to take note of two distinct features in the situation which conspire and give rise to the observed effects. The first is the corpuscular nature of light. The second is the discrete structure of the retina. For light to be perceived, a corpuscle of light has not merely to fall on the retina, but has actually to be trapped by one of the receptors forming the fine structure of the retina and be transformed into an electrical impulse transmitted along the associated nerve-fibres to the cerebral centres involved in the perception of light. Such absorption of the corpuscle and transformation of its energy is essentially a *chance event* as has already been remarked in the preceding chapter. It should be noted in this connection that the

range of illumination in which our eyes can function is enormous. For instance, the illumination of a diffusing screen on which direct sunlight is incident is of the order of 25000 lumens per square metre. It is not pleasant to look at such a brightly illuminated surface, but we can certainly do so for a little while without any disastrous effect on our visual faculties. In the circumstances, we are justified in assuming that the chance of a light corpuscle falling on the retina being trapped and transformed into an impulse carried by the optic nerves is exceedingly small, not greater than one in a hundred, and perhaps even less.

Granting that the perception of light by our eyes is the resultant of the individual chances of absorption of a light corpuscle by one of the receptors in the retina, the way is open to an explanation of the fluctuations of luminosity actually observed. Here, we have to take note of the fact that only an exceedingly small fraction of the number of light corpuscles which reach the surface of a screen and are diffused by it can find their way into the pupil of an eye of the observer. This fraction is the ratio of the area of the pupil to the area of the surface of a hemisphere drawn with an element of area of the illuminated screen as centre and having as its radius, the distance of the observer from the screen. If we take the diameter of the pupil as 5 mm and the screen to be two metres away from the observer, the chance of a light corpuscle from the element of area finding its way to the retina is reduced in the ratio of 1 to 1,300,000. This factor will be further reduced by the very small probability of a corpuscle reaching the retina being actually perceived as light. Further, *to enable the screen to be perceived by the eye as uniformly illuminated, it is necessary that everyone of the individual receptors in the retina should be fully engaged all the time in receiving light corpuscles, absorbing them and passing on the absorbed energy in the form of nervous impulses, and that this process is repeated once in every small fraction of a second of time.* When it is further remarked that in the foveal depression in the retina alone, there are 100,000 individual receptors, it will be realised that even when the illumination of the screen is as high as one lumen per square metre, it is extremely unlikely that the requirements stated above would be fully satisfied. Actually, it may be expected that only a fraction of the receptors (determined by the laws of chance) would be functioning at any given instant. That fluctuations of luminosity over the area of the screen would be observed follows as a natural consequence of these considerations.

Some further remarks: What has been stated above enables us to proceed a little further and to offer a reasonable explanation of the features observed in various circumstances and set forth above. The smaller is the luminous flux incident on the screen, the less would be the proportion of the receptors of vision actually functioning at any given instant of time. In consequence, the larger would be the areas in which variations of brightness would manifest themselves. In other words, the contrasting areas of light and shade would be larger in size, and the contrasts themselves would be more readily perceptible and the changes from

greater or lesser brightness occur less rapidly. An increase of the luminous flux falling on the screen would produce the reverse effects. As the observer moves away from the illuminating screen, the actual number of light corpuscles reaching any particular region of the retina would not alter appreciably. But the image of the fluctuations in the activity of the retina as seen projected on the illuminated screen would be enlarged in proportion to its distance from the observer, and this is what is actually observed. Finally, the very striking nature of the fluctuations observed when the illuminating radiation is in the region of shorter wavelengths becomes intelligible when it is recalled that the corpuscles in this region represent larger quanta of energy and for the same energy are therefore fewer in number, and that, further, the chance of a corpuscle being actually absorbed and giving rise to a visual impulse, is necessarily much smaller in view of the very low luminosity of these regions of the spectrum.

The new physiology of vision—Chapter IV. Corpuscles of light and the perception of form

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The observations described in the preceding chapter provide us with a fresh insight into the nature of vision. Our visual sensations are the resultant of an immense number of discrete processes, each of which is a chance event, viz., an individual corpuscle of light being taken up by a receptor unit in the retina and transformed into an impulse which reaches the centres of perception. The superposition of these unit processes in large numbers does not necessarily result in every trace of their discreteness being effaced. The fluctuations of luminosity seen by an observer on the surface of a uniformly illuminated screen viewed by him are evidence to the contrary. As is to be expected, the character of the observed fluctuations is found to depend on the strength of the illumination of the screen, the distance from which it is viewed and on the spectral character of the illumination.

In the present chapter, we shall concern ourselves with the part played by similar considerations in the normal functioning of our visual organs. The binocularity of vision not only enables us to perceive the form of the objects around us but also to locate their relative positions in three dimensional space. We shall not here enter into this more recondite subject and will confine ourselves to the simpler aspects of vision, viz., the perception and recognition of the form and features of individual objects in two-dimensional space. Even here, we shall, in the first instance, begin by considering cases of a relatively simple type.

Observations with test-charts: Perhaps the most frequent use of vision in daily life is the reading of printed material of various sorts. Constant familiarity enables us instantly to recognise the letters of the alphabet when presented to us. It is, therefore, not surprising that in ophthalmic practice the material commonly made use of for examining vision and prescribing the corrective glasses needed in cases of defective eye-sight consists of sets of letters printed in black on white card, thus providing the maximum of contrast between the object and the background against which it is viewed. In the well known Snellen test-charts, there are in all eleven rows of letters, the first consisting of a single letter of large size, and the others following it containing letters of smaller sizes and in greater numbers. The

standard charts are designed to be set at a distance of six metres between the chart and the observer, this being regarded as representative of distant vision. The sizes of the letters on the chart have been so adjusted that an observer with average normal vision can recognise and read the letters in the eighth line, but cannot proceed further. If he can read the lines beyond the eighth, his vision is better than the average normal. Ability to read the eleventh and last line on the chart indicates a visual acuity twice the normal average, but such cases are relatively rare.

If an ophthalmic test-chart is to serve the purposes for which it is intended, it should be adequately illuminated, either artificially or by ordinary daylight. For an investigation of the relationship between visual acuity and the level of illumination, it is necessary to have an arrangement by which the strength of illumination can be controlled and varied over a wide range. For this purpose, the author makes his observations in a darkened room into which skylight is admitted through a circular window set fairly high up and having a diameter of 25 cm. This window is covered by a large and specially made iris-diaphragm, the diameter of the opening of which can be varied from the full value of 25 cm down to 5 mm as desired, thereby providing for a reduction of illumination by a ratio of 2500:1. The test-chart is set facing the window and at such a distance from the observer that the eighth line of letters can be comfortably read. As the illumination is diminished progressively, the observer maintaining his distance from the chart, successive rows of letters, one after another, become indistinct, then unreadable and finally unobservable. At the lowest level of illumination, even the first large letter on the chart can scarcely be seen. But if at any level of illumination, the observer, instead of remaining at the same position, approaches sufficiently near to the test-chart, the letters become clear again, in other words, the effect of diminished illumination can be set off by diminishing the distance of observation.

The progressive fall in the acuity of vision with diminishing strength of illumination thus manifest is readily understood when it is realised that for perceiving an object clearly, it is necessary that the corpuscles of light reaching the retinae of the observer from all parts of the object are sufficiently numerous to give rise to an integrated perception of its entire form. The feebler the illumination, the less likely it is that this requirement is satisfied. We would then be unable to perceive the whole object, but only see parts of it which vary from instant to instant. In other words, a fluctuating and broken-up picture of the object is presented to us instead of a clear and complete image of it. With any further reduction in the illumination, the visual image would cease to be recognisable and would ultimately tend to disappear.

The foregoing is a statement of what is actually seen of the individual letters on the test-chart and correctly describes their appearance as the iris-diaphragm of the window is progressively closed down. Indeed, at the lowest levels of illumination, the phenomenon of an entire letter disappearing from sight and

reappearing immediately afterwards is often noticeable. We may here raise and answer the question why when the observer comes sufficiently close to the chart, letters which were previously indistinct and even invisible come into view again. The answer is that the image of a letter on the retina is then much enlarged and at the same time, the number of light-corpuscles reaching the image is increased in the same proportion. In consequence, the fluctuations of the image would, relatively to its perceived size, be on a much smaller scale, and the resulting fragmentation of the image would not therefore prevent its form as a whole being perceived and recognised.

The foregoing description and discussion refers to the case of a Snellen chart of the standard size held at a considerable distance from the observer. Essentially similar observations can also be made with charts printed on a reduced scale so that the entire chart can be held at arm's length. The disappearance of the lines on the chart one after another as the illumination is reduced is also noticed in this case. But it is not quite so easy using the smaller charts to observe and follow the fragmentation of the images, as the fluctuations which cause such fragmentation are on a much smaller scale.

Observations with monochromatic light: As in the studies described in the preceding chapter, the use of monochromatic illumination instead of ordinary daylight is strongly to be recommended for the study of visual acuity. Using such light, e.g., the light of a sodium-vapour lamp, it is easy to recognise the relationship between the effects observed on a uniformly illuminated screen and those exhibited by a test-chart carrying printed letters. Putting the two side by side so that they are equally illuminated, it becomes evident that the fluctuations observed in both cases have a common origin and are closely related to each other. The moving areas of light and shade are of approximately the same size in both cases in any particular circumstances of observation. In the earlier chapter, it was remarked that using the $\lambda 4358$ radiations of the mercury arc, the fluctuations visible on a screen uniformly illuminated with such light are extremely conspicuous. It is to be expected that in these circumstances, the visibility of letters on a test-chart should be very low with such illumination. This is indeed made evident by actual observations. The contrast with the much higher visual acuity observed using the light of the sodium lamp is very striking.

Binocular observations of visual acuity: The noteworthy observation was recorded in the preceding chapter that the fluctuations of luminosity on a uniformly illuminated screen are more conspicuous when viewed with only one eye of the observer open (the other being closed) or *vice-versa*. It was remarked that this observation indicates the fluctuations of luminosity as seen by the retinae of the two eyes to be *independent* and the effect of binocular superposition is thereby to diminish their visibility. Having regard to these remarks, it is significant that when a test-chart is viewed under reduced illumination, the visibility of the letters

is notably *improved* by using both eyes. *Per contra*, it is visibly diminished by closing one eye or the other. This is what we should expect if the diminished visibility of the letters is the result of fluctuations in the perceived retinal images. If both eyes are used, the binocular superposition would tend to suppress the fluctuations in the perceived images and thereby to improve their visibility.

Scintillating charts: An effective demonstration of the role played by fluctuations of luminosity in visual acuity and the perception of form is forthcoming when the Snellen charts containing rows of letters of diminishing size are replaced by charts in which the objects under view are all similar to each other and are arranged in regular geometric order. Charts of this kind can be readily prepared on white bristol board using Indian ink to cover up a succession of strips all of equal width, arranged both horizontally and vertically and set at equal intervals. We thus obtain a chart consisting of white squares on a black background, equidistant and all of the same size and arranged in rows and columns forming a regular pattern. It is useful to prepare a number of such charts in which the squares are of different sizes, e.g., 5 mm \times 5 mm, 1 cm \times 1 cm and 2 cm \times 2 cm.

All the three charts may conveniently be set side by side and illuminated in the same fashion, so that they may be readily compared with each other. The monochromatic light provided by a sodium-vapour lamp is well suited for the purpose and by the use of an iris-diaphragm the illumination of the charts may be varied over a wide range of values. When the illumination is sufficient and the observer is not at a great distance from the charts, the white squares on all three charts are seen with clear and sharply-defined boundaries. But when the illumination is progressively reduced, this is no longer the case. The chart with the smallest squares first shows the alterations in appearance and is followed by the two others in the order of the sizes of the squares. The effects of increasing the distance of the observer also follow the same order. The most interesting cases are those in which the squares continue to be visible but with much less than the maximum definition. It is then noticed that the squares fluctuate in brightness, the difference between each square and its nearest neighbours being readily observable. In the case of the chart with the 5 mm squares, the changes in brightness give rise to an effect resembling scintillations. The charts with the larger squares also exhibit curious continuously changing deformations of the form of the white areas, while inside those areas irregular patterns of light and shade are visible; these patterns vary from square to square and also change continuously.

The new physiology of vision—Chapter V. Corpuscles of light and the perception of colour

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The subject of colour is of extraordinary interest and importance. The nature of the colour sensations experienced in various circumstances and the genesis of those sensations are, therefore, amongst the major problems with which the physiology of vision is confronted. In the present chapter these problems will be considered, but we shall restrict ourselves to the specially simple class of cases in which the sensations are those excited by light of spectral purity, in other words, by radiations limited to a narrow range of wavelengths in the spectrum. The sensations excited by spectrally composite radiations present a field of enquiry of a more complex nature. They will be dealt with in later chapters.

That the sensation of colour arises from and is closely related to the corpuscular nature of light is evident from the progression of colour observed in the spectrum. When white light emitted by a solid body held at a high temperature is analysed by passage through some dispersing apparatus, e.g., a prism or a diffraction grating, it appears spread out into a continuous band of colour. If the dispersion is adequate, a great many different colours may be distinguished in it. These colours form a continuous sequence, and since the light isolated from a sufficiently narrow region of the spectrum consists of corpuscles all having the same or nearly the same energy, it follows that each specific colour observed in the spectrum corresponds to a distinct set of corpuscles all having the same or nearly the same energy. The association thereby made evident between the energy of the light-corpuscles and the colour sensations excited by them is clearly of a fundamental nature. It has, of necessity, to form the basis of any attempt to ascertain or elucidate the nature of the sensations of colour.

Luminosity and colour: The visual effect of light reaching the eye is determined by two variables capable of quantitative specification and measurement, viz., the flux of light and its spectral character. We may proceed to associate these two physical variables respectively with the two characters which are noticeable in our visual sensations, viz., the brightness of the light and its chromatic effect. This way of regarding the matter is, however, not free from difficulties. It assumes without proof that luminosity and colour are independent sensations. Actually, it is

possible to take a different view of the situation. While recognising that the visual effect of light is determined by two factors which can be independently varied, we may regard the sensation as being itself one and indivisible. An argument which lends support to this latter view may be based on a consideration of the effect of progressively reducing the flux of light till it reaches the vanishing point, while its spectral character remains unaltered. It is evident that the entire sensation would disappear when the flux of light is zero. This leads us to the inference that luminosity and colour are not independent sensations but are only aspects of one and the same sensation. That we can recognise a difference in brightness and/or a chromatic difference between two sources of light set side by side for comparison is a fact of observation. It shows that the visual effect of light presents certain recognisable characters. But it does not demonstrate that these characters are independent of each other, in other words, that they can be varied without mutually influencing each other.

By the use of appropriate equipment, the radiations appearing as individual lines in the spectra of metallic vapours may be isolated and the visual sensations excited by such light at various levels of intensity may be studied. What has been stated above makes it clear that we would not be justified in assuming that an alteration of the light-flux in such cases would result in altering the observed luminosity but would leave the chromatic sensation unaffected. So far from this being the case, the investigations presently to be described show that the chromatic sensations excited by such spectrally isolated radiations are profoundly modified by variations of the light-flux. The factual situation thus revealed is clearly of fundamental significance in its physiological implications.

Observations with the sodium lamp: In the spectrum of the light emitted by sodium vapour in the commercially available lamps, the yellow lines are so enormously more powerful than the other radiations present that the latter can be ignored. The sodium vapour lamp is thus a very convenient tool for a study of chromatic sensations at various levels of illumination. The lamp is enclosed in a box, and an aperture on one side of it allows the light to emerge and pass through a diffusing screen of ground glass followed by an iris-diaphragm. The opening of the iris can be varied from a diameter of 10 cm down to a few mm. The observations are made in a fairly large room (ten metres square) which can be completely darkened.

A chromatic sensation being a matter of subjective perception, it is essential to provide a means of ensuring that the experiences reported are not of an illusory nature. The following procedure has accordingly been adopted in the investigation. The lamp and the observed are located near each other at one end of the room, both facing towards its further end. A plastic screen of perfectly white material is set up on a stand facing the lamp and the observer so that the light issuing from the lamp falls on the screen. The surface of the screen is smooth and has a good polish. It accordingly reflects a part of the light falling on it and a reflected image of the source of light is seen by the observer. This exhibits a

brilliant orange-yellow colour. Neither the brightness of this reflected image nor its colour shows any alteration when the iris-diaphragm is closed down from the full aperture of 10 cm down to a few mm. Likewise, neither the brightness of the reflected image nor its colour shows any alteration when the screen is moved away from its original position close to the lamp and the observer to the further end of the room.

But the part of the light falling on the screen which enters the plastic material and is diffused backwards, thereby becoming visible to the observer as a general illumination of the screen, behaves quite differently. The strength of this illumination varies enormously with the circumstances. When the iris is fully open and the screen is close to the source of light, it is quite high. As the screen is moved away from the lamp and the observer, the illumination diminishes rapidly. If further, the iris is also progressively closed down, the illumination of the screen becomes extremely feeble. In the various circumstances stated, the observer can compare the colour of the reflected image of the source with the colour of the diffuse illumination of the screen. It then becomes evident that the alterations in the brightness of the diffuse light go hand in hand with changes in the chromatic sensation excited by it. As the brightness falls, the chromaticity diminishes and the diffuse illumination becomes more nearly achromatic. Even when the light diffused by the screen is at its maximum intensity, its colour does not approach in its quality, the rich orange-yellow of the original source. In the final stages, when the illumination of the screen is very weak, the chromaticity persists but is then only barely perceptible.

An alternative procedure which enables the observer to convince himself of the reality of the changes in chromaticity resulting from changes in luminosity is to view an illuminated white card held at arm's length and rapidly to alter the strength of its illumination by the sodium light. This may be done, for instance, by quickly reducing the aperture of the iris-diaphragm. Alternatively, with an iris opening of about 1 cm, the card may be held near the source and then moved away quickly to a greater distance. The reductions in chromaticity thus brought about are strikingly obvious.

Observation with the mercury lamp: Using a double monochromator and the arrangements already described in an earlier chapter, each of the stronger radiations of the mercury arc may be isolated and utilized for observations of the same nature as those detailed above. With the instrument set to pass the light of any selected radiation in the spectrum, the exit-slit of the monochromator when viewed directly from any position by the observer exhibits the colour of the particular radiation quite brilliantly. On the other hand, if the light diverging from the exit-slit falls upon a white card or a white plastic screen and the light diffused by it is viewed by the observer, the colour observed is relatively weak. Indeed, only when the diffusing screen is held very close to the exit-slit is the colour of the diffused light at all comparable with the colour of the light from the

slit as viewed directly. The weakening of colour is thus evident even when the illumination of the screen is still fairly strong. As the screen is moved further and further away from the slit and the illumination becomes weaker by reason of the divergence of the emerging beam, the chromaticity continues to diminish continuously and progressively and the perceived sensation approaches more and more nearly to an achromatic sensation. Nevertheless, the chromaticity continues to be detectable so long as the illumination of the screen can itself be perceived.

It should here be emphasised that though effects of the nature described can be observed with every one of the radiations spectrally isolated from the light of the arc, the rapidity of the chromatic change noticed when the diffusing screen is moved away from the exit-slit is by no means the same for all of them. The most striking and rapid changes are exhibited by the $\lambda 4358$ radiation of the arc appearing in the blue region of the spectrum. Very striking also, though not so rapid, are the changes noticeable with the $\lambda 6150$ radiations in the red region of the spectrum. On the other hand, with the $\lambda 5461$ radiations in the green and the $\lambda 5770-5790$ radiations in the yellow, we have to move the receiving screen much further away from the exit-slit before the chromatic changes are as obvious as with the blue and red radiations. These differences may, at least in part, be explained in terms of the greater visual intensity of the $\lambda 5461$ and $\lambda 5770-5790$ radiations of the mercury arc as compared with the $\lambda 4358$ and the $\lambda 6150$ radiations.

The significance of the results: The highly remarkable but indisputable fact which emerges from the studies which have been described is that the chromatic sensations usually known as the colours of the spectrum fade away and progressively tend towards an achromatic sensation (though they do not actually become such) as the illumination which reaches the observer is continuously reduced. It is evident that we have here an effect of fundamental significance in the physiology of vision. The question may here be asked whether such a striking phenomenon could not be demonstrated in a simple fashion, as for example, by an observer viewing directly the spectrum of a light-source the luminosity of which is progressively diminished. The answer is that the subjective nature of the effect makes it desirable that the arrangements for its observation should be such as to exclude all possibility of error and ensure the reality of the findings reported.

We now turn to the basic question, why should the chromatic sensation excited by spectrally pure radiation fade away as the effective light-flux is diminished? The answer to this may be found in the two preceding chapters in which the perception of luminosity and the perception of form were respectively discussed. In both of those chapters, we were concerned with effects in which the corpuscular nature of light comes visibly into evidence. In both cases also the effects observed become increasingly more conspicuous as the light-flux is diminished; in both cases also, they depend notably on the spectral character of the illumination. The

parallelism in these respects between the effects described in those chapters and those now under consideration is evident. It is quite appropriate therefore that we proceed to find an explanation on generally similar lines.

What the observations indicate is that the chromatic sensations which we normally associate with the different regions in the spectrum demand that the corpuscles of light reach the individual visual receptors in the retina in sufficient numbers and follow each other in such rapid succession as to give rise to a continuous and coherent sensation. These are precisely the conditions in which the fluctuations of luminosity in the field under observation would cease to be noticeable and in which the visual acuity as determined by appropriate tests would reach the optimum value. That the chromaticity is also at its best in these circumstances is readily verifiable by observation. It is found when the illumination is sufficient to meet the most stringent tests for visual acuity, the colour perceived is most brilliant. *Vice-versa*, when the illumination falls and the visual acuity is reduced thereby, the chromatic sensation is noticeably weakened. As the chromatic sensation progressively becomes weaker and weaker by reason of the diminishing light-flux, the visual acuity also suffers and touches very low levels.

The new physiology of vision—Chapter VI. Vision in dim light

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The results which emerged from the investigations set forth in the three preceding chapters are evidently of far-reaching character. They indicate fresh lines of approach to the basic problems which confront us in the physiology of vision. In the present chapter, we shall make use of some of the findings to elucidate the nature and origin of the differences between visual sensations at low and at high levels of illumination. We may begin by mentioning some facts of observation which indicate that there is a real difference in the visual processes operating at those levels.

When an observer who has been out-of-doors enters a dimly lit room, his first feeling is that of finding himself in complete darkness. After a few minutes, however, he begins to perceive the most brightly illuminated objects in the room; later, those which are less bright come into view, one after another. The effect of a prolonged stay in complete darkness is even more striking; the sensitivity of the eye to feeble light is thereby enormously enhanced. *Per contra*, even a short stay in brightly illuminated surroundings suffices to destroy the sensitivity thus generated. We have, as it were, a process of “switching on” of the apparatus which enables the eye to function in dim light. There is also a “switching-off” of that apparatus which results from exposure of the eye to bright light and this is a fairly rapid process.

Chromatic sensations in dim light: Remarkable changes in our ability to perceive colour follow as a result of lowering the level of illumination of the objects under view. This effect may be exhibited in the following manner. A set of five steel plates of the same size may be painted over with enamels of brilliant hues and set side by side in the following order: White, blue, green, yellow and red. The observations may be made in a room which has been darkened and into which skylight can be admitted through a circular window provided with an iris-diaphragm of which the opening can be altered as desired from a diameter of 25 cm down to 5 mm. The illumination of the plates under view can thus be altered over a ratio of 2500:1.

As the iris is progressively closed down, very striking changes are noticed in the appearance of the set of plates. The plate which is red and exhibits that hue

brilliantly when the iris is fully open becomes darker and darker as the illumination is diminished by closing down the iris. The plate then turns black and remains completely black. This, of course, is the well-known Purkinje phenomenon. A perfect contrast with the behaviour of the red plate is provided by the plate which is white. This exhibits no change whatever and remains throughout as the brightest of all the plates. The brilliant colours shown by the yellow, green and blue plates become much less brilliant as the iris is progressively closed down. At low levels of illumination, the yellow plate continues to exhibit that hue but much enfeebled. It also appears more luminous than the other two plates but is inferior to the white plate in that respect. Next in order of brightness is green plate which continues to exhibit a greenish hue. The blue plate appears in the same circumstances to be of a darker hue with a bluish tinge.

The colour-luminosity relationship: The changes in chromatic sensations manifested at low levels of illumination have in the past been sought to be explained on the basis of an assumed duality of the human retina, viz., a day-retina which perceives colour and a night-retina which has only colourless vision; in the day-retina the cones are the receptors of vision, while in the night-retina, the rods perform that function. That this approach to the theory of colour perception cannot be sustained is evident from the facts of observation recalled in an article by the author entitled "Stars, Nebulae and the Physiology of Vision" published in the issue of *Current Science* dated the 20th of May 1964. When we look at the sky by night and fix our attention on any particular star, its image is formed on the foveal region of the retina, and since this contains only cones and no rods, it is cone-vision and not rod-vision that is functioning. The effective surface-temperatures of the stars show a great range of variation. Nevertheless, it is a fact of observation that the vast majority of the stars visible to the naked eye appear merely as specks of light without any hint of colour. But as seen through a telescope with an objective of adequate size and correspondingly great light-gathering power, the colours of the individual stars and the differences between them are much more evident. Then again, the gaseous nebulae, e.g., the Great Nebula in Orion, as seen through small telescopes appears as areas of diffuse luminosity without noticeable colour. On the other hand, as viewed through giant telescopes, they exhibit brilliant and variegated hues. It is thus clear that the factor which determines the observability of colour is the magnitude of the light-flux which reaches the eye of the observer. Hence also, a distinction between rod-vision and cone-vision is irrelevant in this context. In the fifth chapter of this treatise, observations have already been described showing that a change in the level of the illumination of the object under view profoundly influences the chromatic sensations which it excites, thus affording an experimental confirmation of the same result as that emerging from the visual observations in the field of astronomy referred to above.

The colours of the spectrum: A technique has been devised by the author for a critical study of the chromatic sensations excited by a pure spectrum at all levels of illumination. It is both simple and flexible and yields results free from all uncertainty or possibility of error. The observer places himself in a large room which can be completely darkened and in which there are no sources of light present which can disturb or distract his vision. The light under observation enters the room from outside through a long narrow opening of which the actual width can be varied within wide limits. Such an opening is readily provided by a suitable adjustment of the wooden shutters which cover one or another of the windows of the room. The observer sits facing the opening at some considerable distance from it and holds close to his eye a diffraction-grating of good quality, as for instance, one of the replica gratings supplied by the firm of Adam Hilger in London. The observer's field of vision then includes besides the opening itself, the diffraction spectra of various orders on either side of it. The spectral resolution provided by the grating is such that even with these simple arrangements a great many Fraunhofer lines can be seen in the spectra. If the observer is sufficiently far away from the window, the opening between its shutters can be increased by a ratio of 100:1 without any serious loss of purity in the spectra, while their brightness is increased in that ratio. Still larger variations in the light-flux can be obtained by merely choosing the time of the day at which the observations are made. The light of the sky which enters through the opening has practically zero intensity on a dark moonless night. It is much brighter when the sky is lit up by the light of the moon. In daytime when the sun is well above the horizon, it is enormously brighter. During the hours of twilight, before dawn or after sunset, it exhibits a progressive increase or a progressive diminution, as the case may be. The observer is thereby enabled without using any special equipment to study the chromatic sensations excited by the rays of the spectrum at all levels of illumination, ranging from zero upwards to high values.

The results of the study: The diffraction spectra seen when the light of the sun-lit sky is admitted through the opening between the shutters are of the usual type in which the luminosity of the red region of the spectrum is conspicuously greater than that of the blue region. Simple inspection enables the observer to discover for himself some very significant results. For example, with the particular grating employed, the first-order spectrum on one side is very bright and the second-order spectrum on the same side is very weak. Comparison of the two spectra shows that the visible difference in their luminosities goes hand in hand with a notable difference in their chromaticities. This difference is exhibited by every part of the spectrum ranging from the red end to the violet. But the blue-violet regions in the two spectra which are the least luminous show the difference in a particularly striking fashion. Likewise, a diminution in chromaticity can be observed at all points in the spectra of all orders when the illumination is lowered by a large reduction in the width of the opening through which the light is

admitted. The variations in chromaticity as between the spectra of different orders are particularly conspicuous when the observations are made early in the morning or late in the evening when the light-flux reaching the eye of the observer is rather low.

The spectra as seen under "dim-light" conditions, e.g. at night-time using the moon-lit sky present a totally different appearance. They are much shortened, the red region being totally absent. The first-order spectra exhibit a greenish hue for the greater part, while their terminations on either side exhibit slightly different hues. The second-order spectra on either side which are of much lower intensity can be seen but do not exhibit any recognisable colour.

The change in the character of the spectra in passing from high-level to low-level illumination can be followed by making the observations during twilight hours. The changes from one type of spectrum to the other can also be quickly effected and observed by the use of two polaroids between which the diffraction grating is interposed. If the polaroids are in the crossed position, the spectra are completely cut off. By rotating one polaroid with respect to the other, the light is restored and the progressive increase in the brightness of the red region relatively to the rest of the spectrum can be readily followed.

We may sum up the results of the observations as follows. At the higher levels of illumination, the chromaticity of the spectrum colours is profoundly influenced by the magnitude of the light-flux which reaches the eye, falling off rapidly as the light-flux diminishes. This effect is exhibited by all parts of every spectrum. At low levels of illumination, the red end of the spectrum is cut off, as is to be expected in view of the Purkinje phenomenon. But the other spectrum colours continue to be observable even at such levels, though in an attenuated form, their chromaticity decreasing progressively as the level of illumination is lowered.

Observations with colour filters: The studies described in the preceding chapter and in the present one may be usefully supplemented by the aid of colour filters suitably chosen and judiciously employed. The most suitable filters are those which transmit restricted regions of the spectrum and effectively cut off the rest. If such a filter is interposed between the eye of the observer and a diffraction grating in the method of observation described earlier, the overlap of the spectra of higher orders with each other is effectively avoided and it becomes possible for the observer directly to compare with each other the spectra of all the orders. Four or five orders are exhibited on each side by the replica grating, their intensities falling off with increasing order. The fall in chromaticity which goes hand in hand with the decrease in luminosity is then very strikingly exhibited. As all the spectra can be seen simultaneously, this is a highly impressive demonstration of the fact that colour and luminosity are inseparable aspects of our visual sensations and have to be considered together in physiological theory. Four filters suitable for observations of this kind have been used, one transmitting a band at the violet end of the spectrum, the second a band in the blue, the third a band in the green,

while the fourth transmitted the red region in its entirety and cut out the rest of the spectrum. All the four filters exhibit the stated effects in a very striking fashion.

If a colour filter be held in front of an observer's eye and a white surface under daylight illumination is viewed through the filter, the appearance of the surface depends greatly on the actual level of such illumination. These variations can be demonstrated in an impressive fashion by making the observations in a darkened room, the illumination being controlled by the use of a circular window covered by an iris diaphragm, as has been described earlier. The observer should view alternately the window through which the light is admitted into the room and the surface on which the light falls, holding the filter in front of his eye all the time. A striking difference is then observed between the chromatic effects noticed in the two cases. As the iris is progressively shut down, the window as seen through the iris continues to exhibit the same brightness and the same brilliant colour throughout. On the other hand, the chromatic sensation excited by the illuminated surface progressively becomes weaker and weaker and approximates more and more nearly to an achromatic sensation as the iris is shut down.

Finally, mention should be made here of a remarkable effect noticed in observations of the same nature as that mentioned above when a red filter is held in front of the observer's eye and the object viewed under daylight illumination is itself an object of a brilliant red colour, e.g., a plastic sheet of that colour, or a steel plate covered with red enamel. By reason of the Purkinje effect, the surface under observation would appear black if its illumination by daylight is below a certain level. If, however, the illumination is a little above that level, it would continue to be visible, but would exhibit a dark red colour. In these circumstances, the effect of interposing a red filter before the observer's eye and then removing it is a dramatic change in its appearance. Without the filter, the surface appears dark red; as seen through the filter, it seems almost perfectly white.

The new physiology of vision—Chapter VII. The perception of colour in dim light

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The existence in the human retina of the two kinds of structures known respectively as the rods and the cones led to the widespread belief that these structures have different functions to perform; that the cones form the “day-retina” which perceives colours and which adapts itself to darkness quickly but only to a small extent: that the rods on the other hand constitute a “night-retina” which has only colourless vision and a sensitivity which increases but slowly and over a wide range as the period in darkness becomes longer. We have now to consider whether it is possible to reconcile these beliefs—any of them or all of them—with the facts of observation elicited by the author’s studies and set out in the two preceding chapters. The answer to these queries will become evident when the circumstances in which those observations were made are recalled, as we shall presently proceed to do.

The facts which may be grouped together under the description of the colour-luminosity relationship may first be considered. This relationship emerges when the chromatic sensations excited by the individual rays of the spectrum are studied in relation to the magnitude of the light-flux which reaches the retina. The observer views an extended surface on which the light is incident. It is found that as the illumination of the surface is progressively diminished, the chromatic sensation becomes weaker and weaker and tends to approach an achromatic sensation in its character. This effect is manifested by light from all parts of the spectrum and over the entire range of illumination covered by the observations. It is thus clearly a general characteristic of human vision. No question of differentiating between rod-vision and cone-vision can therefore arise in the context of colour perception.

The second group of observations concerns itself with the relative luminosity of the different parts of the spectrum as perceived by the eye at various levels of illumination. The observations are made by a very simple method; the spectrum of the light-source is viewed directly, a diffraction-grating held in front of the observer’s eye enabling this to be done. The features of the spectrum as thus observed are found to be quite different at the higher and at the lower levels of illumination. In the former case, the entire spectrum ranging from the red to the

violet is observed. But, in the spectrum as observed in dim light, the red region is totally absent; the rest of the spectrum which extends into the green and blue-violet exhibits colour in a perceptible measure, though much less impressively than in the spectrum as seen in bright light. These features are perceived only if the observer has adapted his vision by a sufficient stay in semi-darkness to the low level of illumination at which they manifest themselves. In either case, when viewing the diffraction spectra and recognising their characteristics, the observer makes use of the foveal region of his retina which, as is well-known, contains only cones and no rods.

Thus, while recognising that human vision exhibits different characteristics in "bright light" and in "dim light", we have to remark that the facts do not require us to describe them as vision with colour and without colour respectively. Neither do they require us to identify them with the functioning of the cones and the rods respectively. The need for a lengthy period of adaptation which is a characteristic of "dim light" vision is readily explicable. It is clear that the material needed for the perception of very feeble light is only slowly replenished in the retina when the eye is in the dark and that, *per contra*, it is rapidly removed or destroyed when the eye is exposed to bright light. We are under no compulsion to assume that such replenishment is a specific function of the rods in the retina. On the contrary, it seems more probable that this is accomplished elsewhere in the retina and that the material, if present, would be available for use alike by the rods and by the cones. The facts of observations set forth above indeed suggest that this is actually the case. They indicate that the cones can also function in dimlight and in doing so utilize the material present in the retina which makes such vision possible.

Chromatic sensations in dim light: What has been stated above leads us back to a topic which was briefly touched upon in the previous chapter of the work, viz., the colours exhibited by various objects in dim light as compared with their appearance in bright light. It is not possible for us to deal with this topic here at all fully, for the reason that colour as seen in daylight is the sensation resulting from the synthesis by the eye of the whole spectrum of radiations falling upon the object and returned to the eye after scattering or diffusion by the material of which it is composed. The visual synthesis of colour thus coming into play is a great subject in itself and we shall not here anticipate what will appear about it in later chapters. But it is appropriate that a few observations and remarks are recorded here, supplementing what has been said under the same heading in the preceding chapter.

The fact that colour perception is at all possible in dim light is itself both interesting and important. For the observations to possess any real significance, it is necessary that the observer should have adapted himself by a sufficiently prolonged stay in semi-darkness to the low levels of illumination employed. Further, it is necessary that the illumination under which the objects are viewed is itself not stronger than can properly be described as "dim light". To enable this

condition to be satisfied, the observations should be made in a room of which the illumination can be controlled and brought down to the desired low values. The arrangement described earlier—a circular window through which sky-light is admitted and of which the diameter can be reduced by an iris-diaphragm—is well suited for the purpose. A convenient test-object which ensures that the illumination is low enough is a plastic sheet of brilliant red colour having a clean polished surface. When the illumination falling on the sheet is reduced sufficiently, it turns completely black, so much so that a plate of black glass held against it is invisible. It is desirable that the objects under view are also held or viewed against a dark background. This is conveniently arranged by placing them against a plastic sheet of brilliant red colour, or alternatively on a steel plate covered by enamel of a brilliant red colour. As seen in dim light, either of these devices serves the desired purpose in a very satisfactory manner.

A great variety of material offers itself as suitable for studies of the kind indicated. Perhaps the most interesting materials are flowers, by reason of the availability of numerous colours and shades of colour from plants of the same species, thereby enabling some useful comparisons to be made. Roses, for example, can be had which are perfectly white; others are of various shades ranging from the palest to the deepest yellow: other roses exhibit colours ranging between a brilliant orange and a flaming scarlet; roses are also common which are various shades of red, ranging from the palest rose to the deepest crimson. One can arrange a whole series of coloured roses in a row and observe how the observed colours alter as the illumination is progressively reduced down to the dimmest possible.

Useful material for a study of colour at low levels of illumination is also available in the form of the plastic sheets of various hues, the colour in such cases being exhibited by the light diffused within the material, the sheets themselves being more or less perfectly opaque to light and exhibiting a smooth polished surface which does not scatter light. Varied colours and varied shades and depths of colour are readily available. The author had samples of thirty different sorts at his disposal which could be arranged in a regular colour sequence, thereby enabling their behaviours to be readily compared with each other.

We shall content ourselves by briefly stating the general nature of the effects observed in such studies. All objects which are a brilliant red in colour become black and are practically invisible in dim light. *Per contra*, all objects which are white in bright light continue to be white in dim light. This is not such a trivial observation as it might seem to be at first sight. Indeed, it might well be considered to be a remarkable and significant fact that when the entire region of the spectrum which appears red in bright light has been eliminated, the visual effect of the rest of the spectrum as perceived in dim light remains unaffected.

Another noteworthy observation is the behaviour in dim light of objects which exhibit a yellow colour in bright-light. Spectroscopic examination shows that the colour of such objects is the result of the elimination of the blue-violet sector of

the spectrum; the more complete this extinction is, the more brilliant is the yellow. Yellow flowers or other objects exhibiting that colour are conspicuously luminous as seen in daylight. They continue to be luminous objects as seen in dim light and their yellow colour is also readily recognisable in such light. As in the case of white flowers, the elimination of the red region of the spectrum has no perceivable effect on the observed results.

Spectroscopic examination shows that flowers which appear of an orange colour in daylight exhibit a powerful absorption in the green part of the spectrum, the yellow and the red sectors remaining unaffected. In dim light, these flowers are barely visible objects even against a dark background and their colour is scarcely noticeable. These results are not surprising since in the spectrum of dim light, the red sector is totally absent while the green sector which is its most luminous part ceases to be effective by reason of its absorption by the material of the flower.

By far the most familiar objects exhibiting a green colour are the leaves of plants. The hues exhibited by them vary, a greenish-yellow, a vivid green and a dark green being the shades most commonly observed. In a later chapter we shall have occasion to discuss in detail the origin and nature of these variations. Here it is sufficient to remark that after the necessary adaptation of his vision to the dimly lit surroundings, the observer can readily recognise the green colour of leaves and their variations. The highly decorative deep blue flowers of the "Morning Glory" are barely visible in dim light and then exhibit a just detectable bluish hue.

The new physiology of vision—Chapter VIII. The perception of polarised light

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One of the most remarkable of our visual faculties is the ability to recognise polarised light and to locate its plane of polarisation. It is the foveal region of the retina that exhibits this power which, it may be remarked, is limited to light appearing in the wavelength range between 400 and 500 m μ . The fovea is the most useful part of the retina and the blue-violet sector in the spectrum covering this range of wavelengths stands in a category by itself as the most colourful and yet the least luminous part of it. Clearly, therefore, the process by which the fovea is enabled to recognise the presence of polarisation in light appearing in this restricted range within the spectrum and is unable to achieve the same result in other parts of it, merits scientific investigation. Indeed, one may well expect that such an investigation would throw much-needed light on the fundamental aspects of the physiology of vision. The studies of which the results are described in this chapter were undertaken with that object.

Haidinger's brushes: The blue colour of the sunlit sky has its origin in the scattering of sunlight by the molecule of the earth's atmosphere. Skylight accordingly exhibits a high degree of polarisation when observed in a direction transverse to the rays of the sun. As a consequence, observation of the parts of the sky which exhibit the maximum degree of polarisation should enable us to demonstrate the ability of our eyes to perceive and determine the state of such polarisation. The effects thus arising are best looked for in the forenoon of any bright clear morning when the sun is well up above the horizon. The observer should stand with his back to the sun and view the regions of the sky where the maximum of polarisation is to be expected. These regions would evidently lie along the arc of a great circle which runs at a slant across the sky. Scanning this circle rapidly with his eyes, the observer will notice a band along the circle which appears bluer than the rest of the sky and which is bordered on both sides by bands of the same width exhibiting a distinctly yellowish hue. On fixing his attention at a particular part of the circle to his left, it will be found that the colours seen in that region soon fade away from sight. The observer should then turn quickly and fix his attention on the part of the great circle to his right which is

ninety degrees away from the original point of fixation on the left. He will then notice in this region a very striking phenomenon, viz., a dumbbell-shaped blue brush of light having its axis on the great circle of maximum polarisation of skylight and crossing this brush a yellow brush of light of similar shape with its axis transverse to that circle. These brushes are conspicuous when first seen, but when the observer continues to gaze at them, they fade away from sight. He should then again turn quickly to the region on the circle previously viewed. He will then notice in that region a similar conspicuous manifestation of the blue and yellow brushes crossing each other. This alternation between the left and the right can be repeated as often as desired.

Studied in the manner described, the nature and origin of the phenomena become clear. What the observer perceives is an enormously enlarged picture of the foveal region in the retinae of his own eyes projected on the sky and manifesting itself by reason of the visual response of the fovea to the light incident on it. The spectral character of that light, its state of polarisation and the orientation of the plane of polarisation in relation to the fovea are the factors which determine the nature of the picture perceived. The circumstances in which it is observed indicate that the conditioning of the eye by an earlier exposure to polarised light also plays a highly important role. The entire light of the spectrum is polarised, but the part of the spectrum not included in the range of wavelengths between 400 and 500 $m\mu$ behaves quite differently from the part which is included in that range. It is the latter part of the spectrum that evokes a powerful visual sensation in the two sectors of the fovea of which the axis is parallel to the direction of vibration in the incident light. The two other sectors of which the axis is perpendicular to that direction are not thus excited. Since these differences appear only in the blue-violet sector of the spectrum, the visual sensation in the former case manifests itself as a brush of a bright blue colour. In the latter case, the absence of any sensation in the blue region of the spectrum results in only the rest of the spectrum being perceived. The manifestation of a yellow brush crossing the blue brush is thus accounted for.

The blue and yellow brushes and the regions in the fovea which they represent interchange positions when the observer shifts his vision from the part of the sky on his left to another on his right located ninety degrees away from it. The regions of the fovea which are not excited in one case are those excited in the second case and *vice versa*. The sectors are thus conditioned by the first exposure respectively to respond and not to respond to the second exposure. Accordingly, the blue brush and the yellow brush both turn round through a right angle and manifest themselves conspicuously to the observer's vision.

The spectral characteristics: As stated above, the ability of the fovea to perceive polarisation is restricted to the blue-violet part of the spectrum. In other words, polarisation is detectable throughout the spectral range between 400 and 500 $m\mu$ but is unobservable in the region of greater wavelengths. A simple technique by

which these facts can be demonstrated has been devised by the author. A brilliantly illuminated part of the sky (close to the sun) is viewed through the long slit-shaped opening between the two shutters of a window by the observer who takes up a position at a suitable distance from the opening. Holding a diffraction grating before his eye, the observer can view the first-order spectrum produced by it and can direct his vision to any particular part of the spectrum and scan the entire spectrum from end to end. Insertion of a polaroid before the grating results in polarising the light appearing in the spectrum. Two brushes are then seen crossing each other, one of them being a bright brush and the other a dark brush. When the polaroid is rotated, both the brushes rotate together in the same direction as the polaroid. The brushes can be very clearly seen in the blue-violet sector of the spectrum. But they are not observed in other parts of the spectrum.

That the polarisation of light is undetectable by the unaided vision if the wavelength of the light exceeds $500\text{ m}\mu$ also becomes evident when the observer makes use of a colour filter which completely cuts off all wavelengths less than $500\text{ m}\mu$ while freely transmitting greater wavelengths. Glass filters having such a spectral behaviour are commercially available and they appear of a golden-yellow colour by transmitted light. Viewing an extended source of light through such a filter with a polaroid placed in front which can be turned round in its own plane, critical examination fails to reveal any observable brushes in the field of view. *Per contra*, the use of a colour filter that cuts out all wavelengths greater than $500\text{ m}\mu$ and transmits shorter wavelengths enormously facilitates the observation of the brushes. Instead of a blue brush crossed by an yellow brush, we have then a bright brush crossed by a dark brush, both appearing in a field exhibiting the colour of the transmitted light. The contrasts in respect of luminosity then manifested make the whole phenomenon very conspicuous. The axis of the bright brush is parallel to the direction of vibration in the polarised light, while the axis of the dark brush is transverse to that direction.

Techniques of observation: The use of a colour filter to eliminate the unwanted parts of the spectrum and of a polaroid to secure complete polarisation of the light in any desired azimuth makes further critical studies possible. Observations can then be made under controlled laboratory conditions and artificial light sources having the desired spectral characters can also be utilized. By such studies, it can be established that, though restricted to the blue-violet sector of the spectrum, the ability to detect polarisation belongs to the same category of visual phenomena as the perception of light, form and colour and that it stands in the closest relationship with these perceptions. The difficulty which presents itself in the evanescent character of the phenomenon can be overcome by the adoption of a suitable technique. Holding the colour filter together with the polaroid in front of his eye, the observer should view an extended source of light. The polaroid should be held at first in a particular orientation and then smartly turned round in its own plane through a right angle. It should then be held in the new position

for a little while and later turned back again to the original position. These movements may be repeated as often as desired. Immediately after the polaroid is turned into a new orientation, the brushes are seen at their best, a bright brush along the direction of vibration in the transmitted light and a dark brush in the transverse direction. The brushes fade away soon, but they reappear in full strength in the new position when the polaroid is turned again through a right angle.

The extended sources of light needed for the study are most conveniently accessible out-of-doors, sunlit clouds being the most luminous. Next in order comes skylight, the brightness of which varies enormously with the part of the sky under observation, as also with the time of the day. In the vicinity of the sun, especially when it is covered by a thin haze, skylight can be extremely brilliant. Further away from the sun, the luminosity falls off rapidly. It also becomes very weak in the twilight hours. Indoor observations may also be made using screens which receive their light from open windows. If the screen employed is of the type used for projection work, consisting of a great number of tiny glass-balls embedded in a plastic sheet, a fairly high luminosity may be achieved. Other screens are, of course, less satisfactory. It should be remembered that the combination of a blue-filter with a polaroid transmits only a very small part of white light. The need for a high intrinsic luminosity when an extended source of light is viewed through such a combination is obvious.

For observations indoors with monochromatic light, the most suitable source is a powerful mercury arc lamp of the type used in street lighting. This should be enclosed in a box of suitable size which is provided with an exit window of sufficient area for the emergence of the light. A glass cell containing cuprammonium solution which covers the exit aperture makes an effective filter. It transmits the $\lambda 4358$ radiations and cuts out all longer wavelengths. The light emerging through the filter may be received on a ground-glass screen, the observations being made on the light emerging through it. Alternatively, the light may be received on an opaque diffusing screen, the surface of the latter being viewed by the observer at any convenient angle. This, of course, is a much less efficient source of light than the ground-glass screen which operates by transmission. No colour filter is necessary in either case, only the polaroid being held by the observer before his eye. By varying the distance of the ground-glass sheet or of the diffusing screen from the exit-aperture of the source, a very wide range of strength of the illumination may be obtained.

Results of the investigation: When the techniques of observation described above are made use of, it becomes immediately apparent that the perception of polarisation is only possible when the source under observation has a fairly high luminosity and that it becomes more and more difficult as the luminosity of the source is progressively diminished. Finally, a limit is reached below which the phenomenon cannot be observed at all. The progressive deterioration in visibility

is the result of a diminishing contrast between the luminosities of the dark and the bright brushes seen in the field of view of the polaroid. A stage is reached when by reason of such diminishing contrast, the brushes are barely perceptible and finally become altogether invisible.

The observations made using the $\lambda 4358$ light of the mercury arc in the manner described above make it clear that the falling off in the visibility of the brushes as seen through the polaroid takes place in the same range of luminosities of the field as the progressive weakening of the chromaticity and the diminution in visual acuity described and discussed in the earlier chapters of this work. The parallelism between these phenomena is close and may indeed be described as a semi-quantitative relationship. That the perception of polarisation belongs to the same category as the perception of form and the perception of colour is thereby clearly established.

We may now sum up the observations described above and the conclusions which have resulted in the following series of propositions: (I) The perception of the polarisation of light in a luminous field is limited to the blue-violet sector of the spectrum, viz., the wavelength range between 400 and 500 m μ . (II) The perception takes the form of two crossed brushes which are bright and dark respectively, the bright brush running parallel to the direction of vibration in the polarised light, and the dark brush transverse to that direction. (III) The brushes appear in the field of view which corresponds to the location of the fovea in the retina. They rotate with the plane of polarisation when the latter is rotated. (IV) The contrast in luminosity between the bright and dark brushes diminishes till they finally become invisible when the luminosity of the field is diminished progressively to a low level. (V) There is a complete parallelism between the behaviour just described and the weakening in chromaticity and the fall of visual acuity in the blue-violet region of the spectrum which accompanies a diminishing strength of illumination. (VI) The perception of polarisation thus emerges as an integral part of the same visual process which makes the perceptions of light, form and colour possible in the blue-violet sector of the spectrum. (VII) The materials present in the fovea which activate the perception of light in the blue-violet part of the spectrum are disposed with a high degree of radial symmetry around the centre of the fovea.

In the succeeding chapter, we shall return to a more detailed consideration of the results stated in these propositions.

The new physiology of vision—Chapter IX. The structure of the fovea

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The preceding chapter commenced with an account of the author's studies of the phenomenon known as Haidinger's brushes seen when the polarised light of the sky is viewed by an observer. Investigations of the same phenomenon under controlled conditions and especially the studies in which monochromatic light was made use of showed clearly that these brushes have a physiological origin and represent a visual perception of the polarisation of light which takes its place along with the perception of form and the perception of colour as one of the special faculties associated with human vision. In the present chapter we shall concern ourselves with the nature of the physiological mechanism which makes the perception of polarisation possible.

It is a remarkable circumstance that though the Haidinger phenomenon has been known for over a century, its importance in relation to the physiology of vision remained unrecognised. Largely, this was due to the general acceptance of an explanation of the phenomenon suggested long ago by Helmholtz, viz., that it is an effect arising from the dichroism of material contained in the macular region of the retina. This explanation, if correct, would make the brushes a physical curiosity having no physiological significance. It is therefore appropriate here to point out that the explanation given by Helmholtz is wholly untenable. This becomes evident when we examine the assumptions on which that explanation is based and also when we compare its consequences with the actual facts of the case.

As already stressed in the preceding chapter, special techniques are necessary for the visual perception of polarised light to manifest itself in an impressive fashion. One of the essentials is the use of a colour filter which cuts out all light having a wavelength greater than $500\text{ m}\mu$ and transmits freely the region of the spectrum having shorter wavelengths. The luminosity of the field as seen through such a filter combined with a polaroid should also be adequate. When these requirements are satisfied, the field exhibits a bright brush running parallel to the direction of vibration of the light and a dark brush transverse to the direction of vibration. Employing the proper technique, we observe that the brush running transverse to the direction of vibration is completely dark.

If the facts of observation indicated above are to be explained on the assumption that the material of the retina in its foveal region has a radially symmetric structure which exhibits dichroism, it would be necessary for the absorption of light by the material to be effective and indeed total for optical vibrations along directions transverse to the radii of the structure and over the entire wavelength range between 400 and 500 m μ . Further, there should be no absorption at all for directions parallel to the radii of the structure. These assumptions are inadmissible for the following reasons. In the first place, the retina being a thin membrane and especially thin in the region of the fovea, the presence in it of sufficient absorbing material completely to block out the entire spectrum between 400 and 500 m μ is scarcely possible. Indeed, our eyes would then be unable to perceive the blue light of the spectrum. Another cogent objection is the known behaviour of fibrous materials dyed with organic dye-stuffs. In numerous cases where the dye-stuffs have elongated molecules, the dyed fibres do indeed display marked dichroism. But in all such cases, the strong absorption is manifested for directions of vibration *parallel* to the length of the fibres and not for directions *transverse* to them.

That an explanation of the brushes as a phenomenon of a purely physical origin is inadmissible becomes even clearer when we recall the observed features which indicate its physiological origin. The diminishing visibility of the brushes when the illumination of the field falls off and their disappearance at low levels of brightness puts the phenomenon in the same category as other aspects of our visual faculties. Striking evidence for their physiological nature is also forthcoming from the fact that an earlier exposure of the eye to polarised light has a great effect on their visibility. Indeed, such exposure can even result in the brushes being seen reversed when the polaroid is removed and the light incident on the eye is unpolarised. To exhibit this effect, the observer should hold the colour filter and polaroid before his eye and view a field which is adequately luminous for a sufficient interval of time to allow the brushes seen at first completely to fade away. He should then suddenly remove the polaroid, but allow the colour filter to remain in place. *He will then see the brushes once again but turned through a right angle.* In other words, the fovea then perceives with enhanced brightness that part of the incident unpolarised light which was cut off by the polaroid when it was in place before the observer's eye.

The carotenoid pigments: That the power to recognise polarised light and to locate its plane of polarisation is exhibited by the foveal region of the retina and that it is limited to the blue-violet sector of the spectrum indicates that the brushes arise as a consequence of some special features in the distribution within the fovea of the material which enables us to perceive light in that part of the spectrum. We have, therefore, firstly, to identify the nature of that material and secondly, to find how it is distributed within the fovea.

One of the very striking features of the visible spectrum is the rapidity of the

transition from the blue into the green region. The transition takes place within a range of some $20\text{ m}\mu$ and is centred around the wavelength $500\text{ m}\mu$. We may infer from this that the material which activates the perception of light in the blue-violet sector of the spectrum has an absorption which falls steeply from a large value to nearly zero at $500\text{ m}\mu$. The absorptive power should also be large in the spectral region between 400 and $500\text{ m}\mu$ and should drop down to low values for wavelengths less than $400\text{ m}\mu$. Two pigments which are known to exhibit these features in absorption are β -carotene and dihydroxy- α -carotene. They are plant pigments almost universally present in the green leaves of plants. They find their way into the human body as the result of the consumption of various food products and are present as colouring matters in the serum of human blood. β -carotene and dihydroxy- α -carotene differ distinguishably in their spectroscopic behaviour. The former is optically inactive, being symmetric in its structure. The latter substance which we shall hereafter refer to as xanthophyll exhibits optical activity as its structure is asymmetric. The two substances also differ by reason of β -carotene being a precursor of vitamin A, whereas xanthophyll is not.

Both β -carotene and xanthophyll have been reported as having been found in the human retina. We shall not here pause to discuss which of the two should be identified as the pigment present in the retina enabling us to perceive bright light in the blue-violet range of the spectrum. It is not necessary to discuss that issue here, since they both have elongated molecules and possess the optical behaviour which could provide an explanation for the perception of polarised light.

The distribution of the pigments in the fovea: The fovea is a circular depression in the retinal membrane having a diameter of about 1 mm . Its structure exhibits some very special anatomical features. It is densely packed with a mosaic of the visual receptors known as cones. In this region these cones are much elongated and have a much smaller cross-section than elsewhere. The smaller thickness of the retina in the foveal region is the result of several nervous layers present in other parts of the retina being either absent or greatly reduced in thickness in the foveal depression. In this region, also, the nerve fibres connected with the cones are pushed to one side and run an oblique course, except at the very centre of the foveal depression where they form a criss-cross pattern. Thus, if we exclude this central region, the fovea exhibits a radially symmetric structure by reason of the disposition of the nerve-fibres leading away from the mosaic of cones which fills the pit in the retina.

The carotenoid pigments have highly elongated molecules. β -carotene and xanthophyll have respectively the chemical formulae $\text{C}_{40}\text{H}_{56}$ and $\text{C}_{40}\text{H}_{56}\text{O}_2$. Apart from the two end groups which are different in the two cases, each molecule in these compounds consists of a long chain of carbon atoms held together by an alternation of double and single bonds of which there are nine pairs. It is this structure that enables the molecule to exhibit an absorption stretching far into the visible region of the spectrum from its violet end up to and inclusive of the blue

sector. The geometry of the structure would necessarily lead to this absorption having selective directional properties, being confined to directions of vibration parallel to the long chain and absent for vibrations in directions transverse to that chain.

Highly elongated molecules such as those of β -carotene and xanthophyll finding themselves in an environment of nerve-fibres disposed with radial symmetry in the regions of the foveal depression around its centre may be expected to align themselves parallel to the nerve-fibres and hence also to exhibit a radial symmetry in their disposition. Jointly as a result of such disposition and the optical characters indicated above, it would follow that the absorption of the light by the molecules would be effective for directions parallel to the radii and would be absent for vibration directions transverse to the radii. If the energy of the light corpuscles thus taken up is passed on to the cones nearest to them, the result would be the perception of light for vibration directions parallel to the radii and the absence of such perception for vibration directions transverse to the radii. In other words, in the field of view corresponding to the foveal region of the retina, we would observe a bright brush running parallel to the direction of vibration in the polarised light and a dark brush running transverse to the direction of vibration. This is actually what is observed.

We may remark that the explanation set forth above would cover the details of the picture actually perceived by the observer. It may be mentioned that a colour filter well suited for such observations is a solution of cuprammonium of which the strength is so adjusted that it cuts off the green, yellow and red of the spectrum completely without any sensible absorption in the blue and the violet. A glass tube 3 cm in diameter and 1 cm long fitted with flat end plates and filled with the solution makes a very efficient filter. With the cell and a polaroid held up against the bright sky the configuration of the brushes can be very conveniently studied. It is readily verified that the dumbbell-shaped brushes are confined to a region in the field of view corresponding to the part of the fovea where the nerve-fibres as shown in the anatomical drawings run obliquely. The region corresponding to the very centre of the fovea where the dark and bright brushes cross, is, of course, never quite dark. Its appearance alters with the orientation of the observing polaroid to a certain extent. This indicates that the molecules of the pigment in this region have preferred orientations.

The new physiology of vision—Chapter X. The major visual pigments

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The two preceding chapters of this treatise dealt with the part of the spectrum in the wavelength range between 400 and 500 $m\mu$ and elucidated the nature of the visual process by which the colours ranging from the blue to violet in that region are perceived. We next proceed to explore the rest of the spectrum in the wavelength range between 500 and 700 $m\mu$ with a view to discover what the characters of the spectrum in this region can reveal to us regarding its origin.

Visual inspection enables the spectrum between 500 and 700 $m\mu$ to be divided roughly into three parts. The first part between 500 and 550 $m\mu$ may be described as the green sector of the spectrum. In the second part which ranges between 550 and 600 $m\mu$, we observe a rapid progression of colour, from green to a greenish-yellow and then to a pure yellow and beyond this again to an orange-yellow hue and then orange. The third part of the spectrum between 600 and 700 $m\mu$ exhibits colours ranging from orange to crimson red through various intermediate hues. The colour sequence thus summed up has in the past been sought to be explained as the result of the superposition of the “fundamental” sensations of green and red respectively, their relative importance varying over the range, green being dominant at one end and red at the other. That this view is erroneous and needs to be rejected becomes clear when the actual facts of the case are set out and we consider their theoretical significance.

The most striking feature of the spectral range between 550 and 600 $m\mu$ is the appearance within that range of a strip exhibiting a pure yellow hue. This colour presents no similarity either to the green or to the red of the spectrum, while the colours observed on either side of the strip may be described as a superposition upon a pure yellow sensation of weaker green and red sensations respectively, their proportion to the yellow increasing as we move away from the wavelength at which the sensation perceived is pure yellow. It may be remarked also that the pure yellow appears in the spectrum in a region where the luminous efficiency is very high and indeed not much less than the maximum.

The facts stated above justify us in recognising the wavelength range between 550 and 600 $m\mu$ as that in which yellow is the dominant sensation. We may also justifiably infer that the yellow sensation results from the presence in the retina of

a pigment which has an absorption peak at the point where the pure yellow sensation manifests itself in the spectrum. Thus, instead of relegating the yellow of the spectrum to the position of a minor or secondary sensation, we accord to it its rightful place as the principal or major visual sensation, while blue, green and red which appear in the parts of the spectrum where the luminous efficiency is smaller and which are indeed the most colourful parts of the spectrum should nevertheless be considered as playing only a minor role in vision. The identification of the visual pigment which functions as the receptor of the yellow in the spectrum accordingly assumes very special importance.

The statement that yellow is the major visual sensation is no more than an explicit recognition of the factual situation. Inevitably, therefore, such recognition is essential for a satisfactory or successful elucidation of the entire body of visual experiences in the field of colour. In particular, when we examine the hues exhibited by various objects in daylight and seek to correlate them with the spectral character of the light diffused or scattered by the object and reaching the eyes of the observer, we find that the presence or absence of the yellow in that spectrum plays the determining role. We shall not here enter more deeply into this subject, as it will be dealt with very fully in later chapters under the heading of the visual synthesis of colour. In the present chapter, we shall concern ourselves principally with the identification of the visual pigment in the retina which enables us to perceive the yellow sensation. For this purpose, we shall consider the characteristics of the spectrum in greater detail.

Hue discrimination in the spectrum: As has already been remarked, a rapid progression of colour is noticeable in the spectral range between 550 and 600 m μ . Many authors have determined the minimum change of wavelength necessary at various points in the spectrum to produce an observable change of hue. There is general agreement that the shift of wavelength needed is everywhere rather small except near the very ends of the spectrum. It is exceptionally small at two particular points in the spectrum; one of them is at 490 m μ where the blue of the spectrum changes over rapidly to green. The other point is at 579 m μ where the spectrum exhibits a pure yellow hue, the observed colour changing rapidly to a greenish-yellow and to an orange-yellow respectively on the two sides of it.

Figure 1 reproduces the results of an extremely thorough and accurate study of hue discrimination made at the Bureau of Standards in Washington by E P T Tyndall, and Presented as a graph in a paper by that author (*J. Opt. Soc. Am.*, **23**, 15, 1933). It will be noticed from the graph that the least perceptible difference in wavelength reaches its minimum value of 0.5 m μ at 579 m μ . That this is exactly where the spectrum exhibits the pure yellow colour is readily verified by observation. Visual comparison in a wavelength spectrometer of the two lines of the mercury arc spectrum appearing at 5770 and 5790 Å respectively reveals that the two lines differ noticeably in colour, the former appearing distinctly greenish in hue, while the latter appears as a perfect yellow. Placing a marker in a

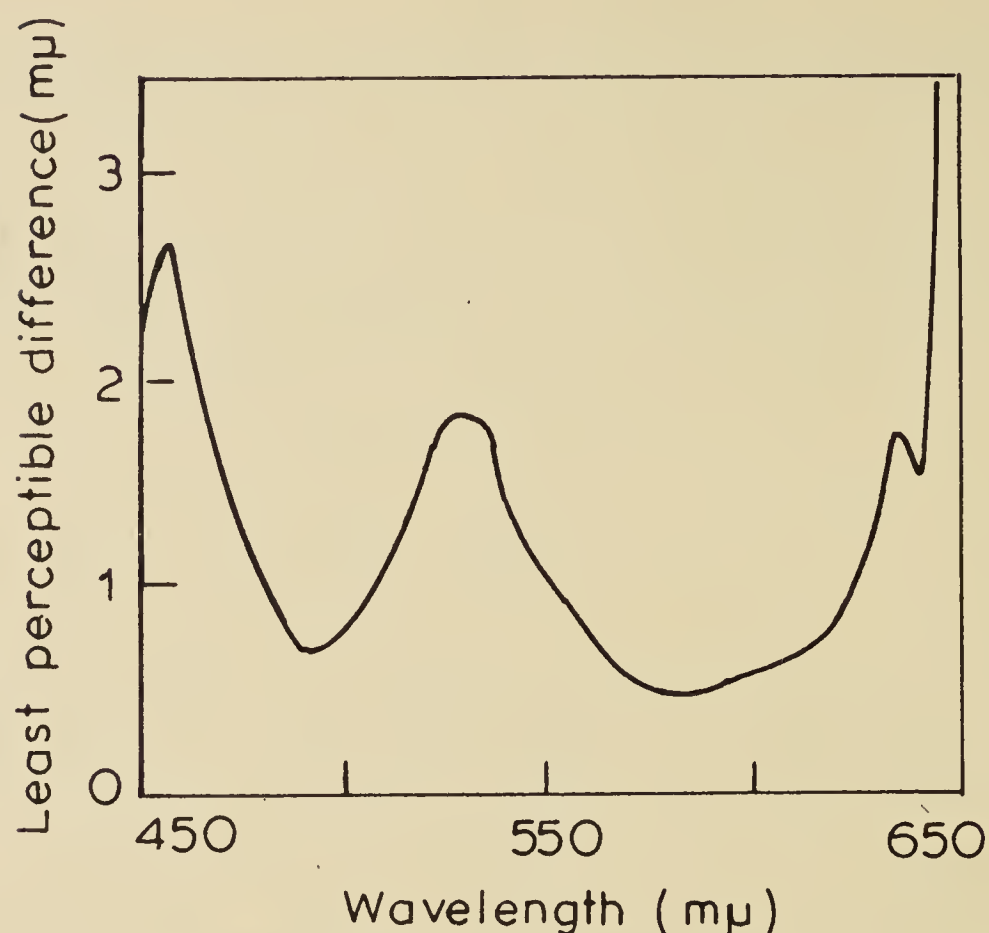


Figure 1. Curve of hue discrimination.

continuous spectrum at the point separating the greenish-yellow from the orange-yellow regions and taking the average of a series of readings, the mean comes out as $579.5 \pm 0.5 \text{ m}\mu$. This agrees very closely with the point in Tyndall's graph at which the power of hue discrimination is at its highest.

It is evident from what has been stated above that the curve of hue discrimination is of great importance in its bearing on the visual processes which result in the perception of colour. It is necessary, however, to consider its indications along with those furnished by the curve exhibiting the variations of luminous efficiency over the visible spectrum. Figure 2 exhibits the form of that curve for foveal vision as actually determined. It will be seen that the luminous efficiency reaches its maximum value at $565 \text{ m}\mu$. But as the efficiency falls off from the maximum more slowly towards greater wavelengths, the efficiency in the yellow at $580 \text{ m}\mu$ is not markedly smaller than the maximum. On the other hand, it will be seen from the figure that the luminous efficiency falls to much smaller values at 530 and $630 \text{ m}\mu$ which are the wavelengths at which the colours in the spectrum are respectively pure green and pure red.

The remarkably high power of colour discrimination exhibited at $579 \text{ m}\mu$, also to a lesser extent on either side of $579 \text{ m}\mu$, is a clear indication that these features have their origin in a powerful absorption by a visual pigment having a well-defined peak of absorption at $579 \text{ m}\mu$. But the maximum of luminous efficiency appears at $565 \text{ m}\mu$ and not at $579 \text{ m}\mu$. Likewise, the hue discrimination curve exhibits a markedly asymmetrical course, running steeply between 550 and $579 \text{ m}\mu$ and much less steeply between 579 and $600 \text{ m}\mu$. These features indicate

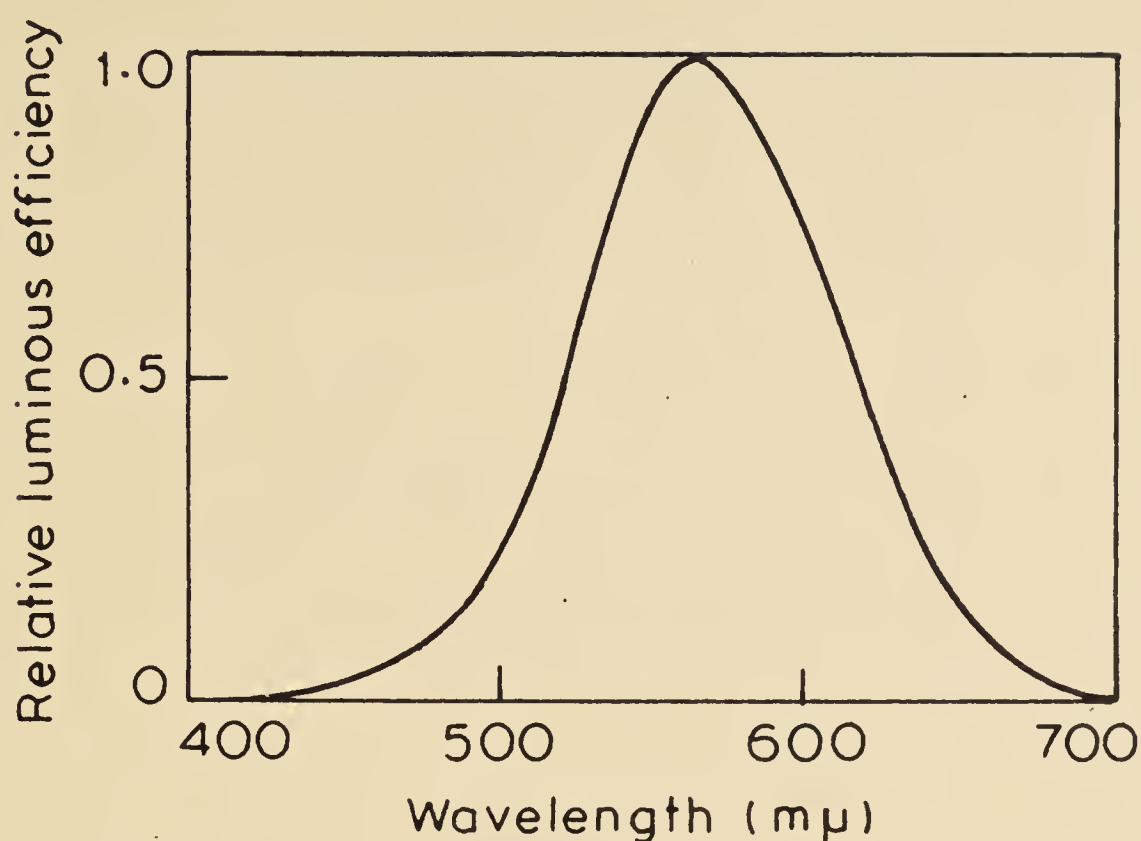


Figure 2. Luminous efficiency in the spectrum.

that other visual pigments also play a not unimportant role in these spectral regions.

Identification of the principal visual pigment: The blood-pigment heme in its various forms is known to exhibit an extremely powerful absorption of light in the spectral range with which we are now concerned. Since the presence of heme in one form or another within the substance of the retina can be safely assumed, we may proceed to examine whether its known spectroscopic behaviour can furnish a clue to the explanation of the facts of colour perception in human vision.

Heme is present in human blood principally as the compound known as oxyhemoglobin which gives it a red colour. The addition of a drop or two of blood to water contained in a cuvette results in the exhibition of a powerful absorption of light. Examination through a spectroscope reveals a sharply-defined dark band at 579 mμ and a much broader and weaker absorption band around 546 mμ. Reduction of the pigment to the form of hemoglobin by the addition of a little sodium dithionate results in a remarkable change in the characters of the absorption. It then manifests itself as a diffuse band of which the maximum may be located around 555 mμ. These facts are clearly brought out in figure 3 in which the absorption curves of oxyhemoglobin and hemoglobin determined spectrophotometrically have been exhibited.

The figures have been copied from a paper by David L Drabkin appearing in the *Barcroft Memorial Volume on Hemoglobin* (Butterworth's, London, 1949). In another paper appearing in the same publication, Felix Haurowitz has reproduced spectrum photographs exhibiting similar features; the positions of the

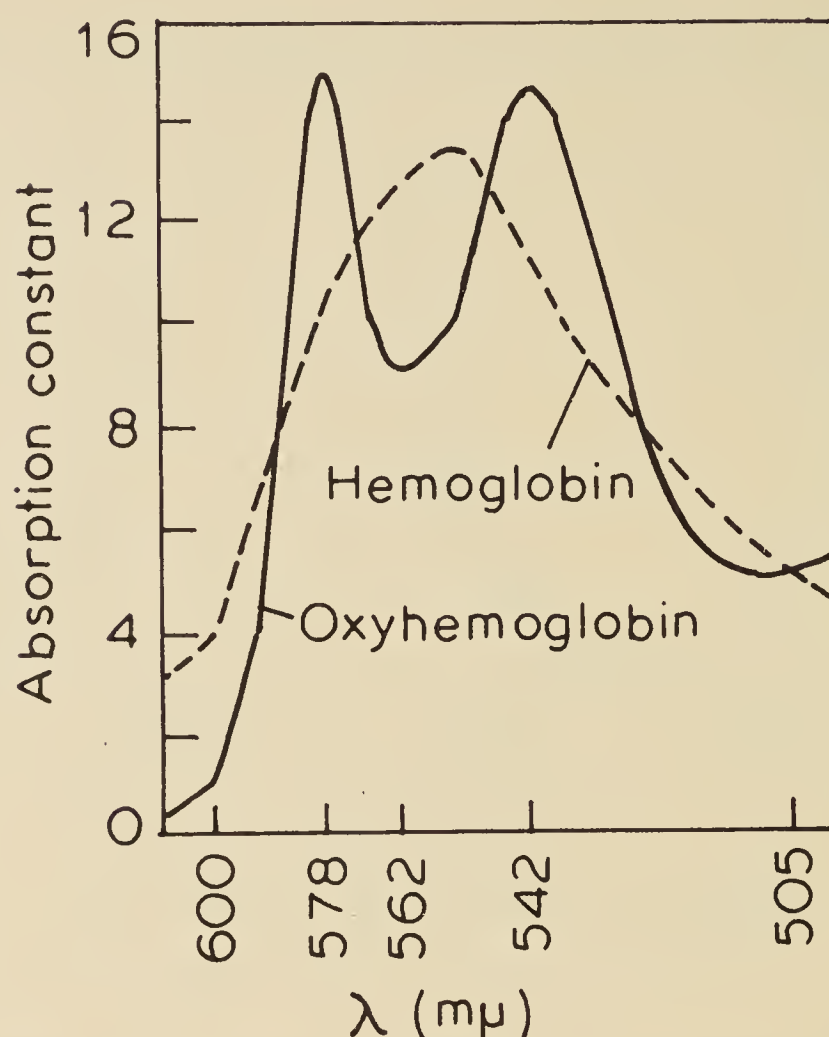


Figure 3. Absorption curves of the blood pigments.

absorption bands of oxyhemoglobin have been marked therein as 579 m μ and 546 m μ respectively.

The exact coincidence of the absorption at 579 m μ exhibited by oxygenated blood with the position in a continuous spectrum of the strip exhibiting a pure yellow colour can be readily verified by holding a cuvette containing water to which a few drops of blood have been added behind the eye-piece of a wavelength spectrometer and viewing a continuous spectrum through it. The absorption band just covers the yellow strip in the spectrum, while measurements with the wavelength drum give the position of its centre as 579 m μ . The inference appears fully justified that the heme pigment in the fully oxygenated form is present in the human retina and that it is indeed the principal visual pigment which enables us to perceive the most highly luminous part of the spectrum. This inference is further confirmed and reinforced when it is remarked that the sharpness of the absorption band at 579 m μ and its great intensity are matched by the narrowness of the strip in the spectrum exhibiting the pure yellow colour and the very high luminous efficiency of the part of the spectrum in which it appears.

The other visual pigments: As has already been remarked, the heme pigment in its oxidised form would not suffice by itself fully to explain the observed characteristics of the spectrum even within the restricted range of wavelengths between 550 and 600 m μ in which yellow is the dominant sensation. To obtain a complete

picture of the situation, we have to consider also the wavelength range between 500 and 550 $m\mu$ and the range between 600 and 700 $m\mu$. In these two ranges, the predominant colour sensations are those of green and red respectively. It may reasonably be inferred that we are also concerned with two other visual pigments whose contributions to the luminous efficiency are important respectively in these two regions.

It is well-known that there are two other pigments chemically related to oxyhemoglobin which are known respectively as hemoglobin and hemiglobin. The first of these results from the action of reducing agents on oxyhemoglobin and the second by its autooxidation. It may therefore reasonably be assumed that the human retina contains three pigments based on heme whose spectroscopic behaviours are respectively similar to oxyhemoglobin, hemoglobin and hemiglobin.

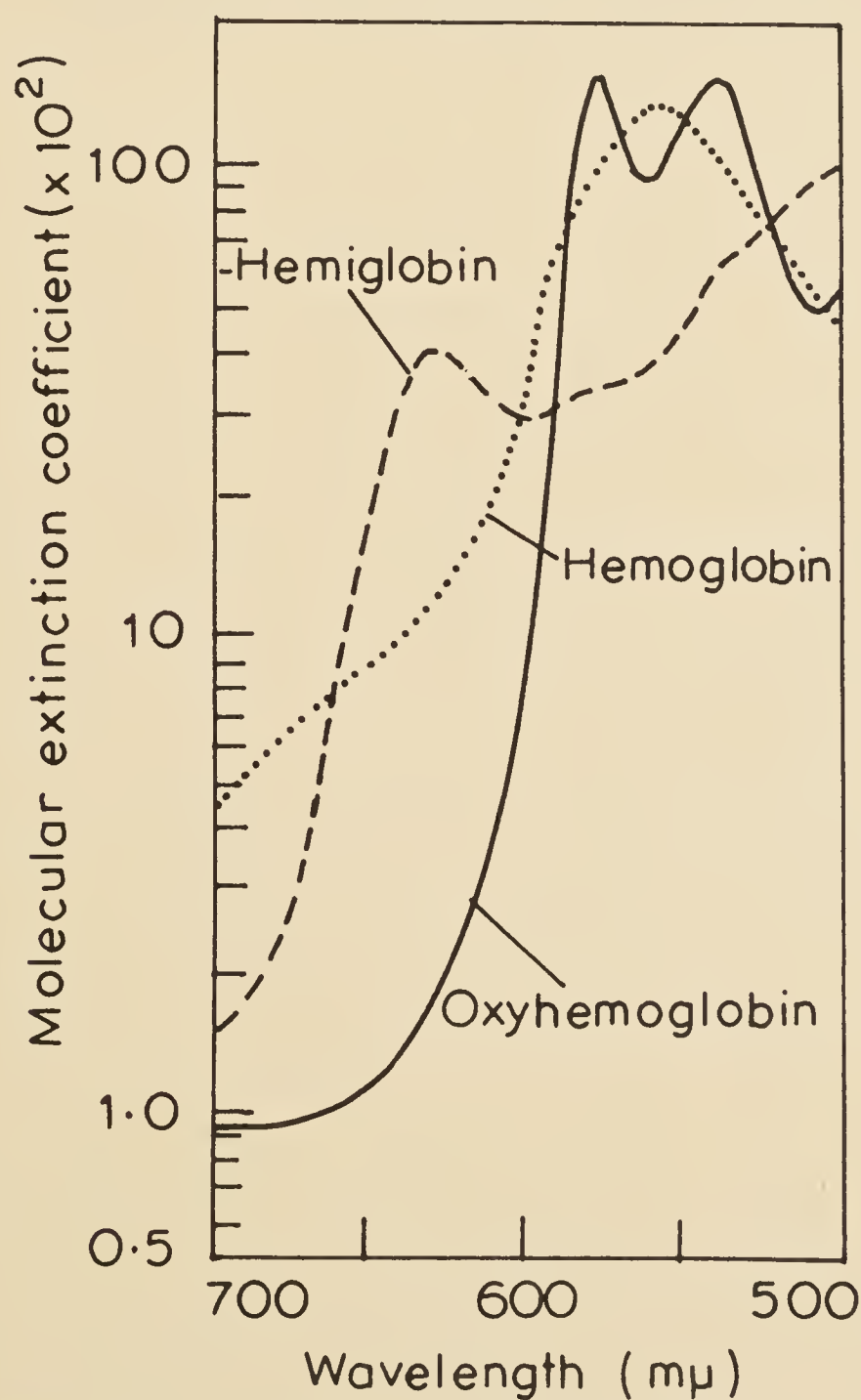


Figure 4. Molecular extinction coefficients of heme pigments.

Figure 4 exhibits the molecular extinction coefficients of these three pigments over the wavelength range between 500 and 700 $m\mu$, reproduced in part from the plate at the end of the book by Lemberg and Legge on "Hematin Compounds" (Interscience, New York and London, 1949). The proportions in which these or the analogous pigments are respectively present in the retina would naturally determine their contributions to the perception of luminosity and colour in the spectrum. In a general way, it can be seen that the superposed effects of the three pigments would explain the observed characteristics of the spectrum in respect of colour and luminosity over the range of wavelengths between 500 and 700 $m\mu$. Particularly noteworthy is the fact that a steep drop in the molecular extinction coefficient of hemoglobin appears at about 630 $m\mu$ (*see* figure 4), while there appears in figure 1 a sharp dip in the hue-discrimination curve at about the same wavelength. A steep drop in the molecular absorption coefficient of one of the visual pigments operating in this region would necessarily result in a marked improvement in hue discrimination at the same wavelength.

The new physiology of vision—Chapter XI. The carotenoid pigments

SIR C V RAMAN

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The carotenoids are a group of carbon compounds which owe their colours to a special feature in their molecular structure, viz., the presence of numerous conjugated double bonds forming an elongated chain of carbon atoms joined together by such bonds. Many carotenoids are to be found occurring naturally. Thirty of these compounds of which the structure has been fully elucidated by chemical investigation are listed in the well-known treatise on the carotenoids by Karrer and Jucker (Elsevier, 1950). Their structural formulae have there been shown in tabular form, and supplemented by another table setting out their classification as derivatives of lycopene and the three known carotenes. Of particular interest are twelve photographs in colour reproduced towards the end of the treatise. These pictures show the forms of the crystals of various carotenoids deposited from solution in appropriately chosen organic solvents.

Amongst the thirty naturally occurring carotenoid pigments of known chemical constitution listed by Karrer and Jucker, two are of particular interest in the present context, viz., β -carotene and xanthophyll. Their chemical formulae are respectively $C_{40}H_{56}$ and $C_{40}H_{56}O_2$. The chemical composition of xanthophyll is indicated by its formal description as dihydroxy α -carotene. Both of these carotenoids are to be found widely distributed in nature. They appear invariably in the green parts of living plants as accompaniments of chlorophyll and presumably therefore play special roles in photosynthesis. Both carotenoids find their way into the human body by way of the food products consumed by the individual. They have been located in human blood serum, in fat tissues, in milk fats, in the liver and in the human placenta. β -carotene is of special importance in human physiology by virtue of its being a precursor of vitamin A which is essential for human health. Xanthophyll, on the other hand, does not serve as a precursor of vitamin A. The reason for this difference is intelligible. β -carotene has symmetric molecules which in appropriate circumstances can split in two equal fragments, each of which by the addition of a water-molecule acquires a terminal hydroxyl group and becomes a molecule of vitamin A. Such a splitting could scarcely be expected to occur in the case of xanthophyll as this substance

has unsymmetrical molecules in which a hydroxyl group is already present in each of the closed rings at the ends of the molecule.

Spectroscopic behaviour of the carotenoids: Towards the end of the treatise by Karrer and Jucker appear 28 figures in which the light-absorption curves of numerous carotenoids dissolved in organic solvents are reproduced. A study of these figures is highly illuminating. With some significant exceptions, the absorption by these pigments appearing in the visible region of the spectrum is restricted to its blue-violet sector, in other words, to the wavelengths between 400 and 500 $m\mu$. Another general feature is the appearance within this range of the spectrum of alternate maxima and minima, there being usually three maxima of absorption. Following such alternations, there is a steep drop in absorption as we proceed towards longer wavelengths, and this is followed by a feeble absorption extending a little beyond 500 $m\mu$ before it finally vanishes. Towards shorter wavelengths, there is also a fall which is distinctly less rapid, the absorption becoming weak at 400 $m\mu$ and weaker still in the near ultraviolet. These features

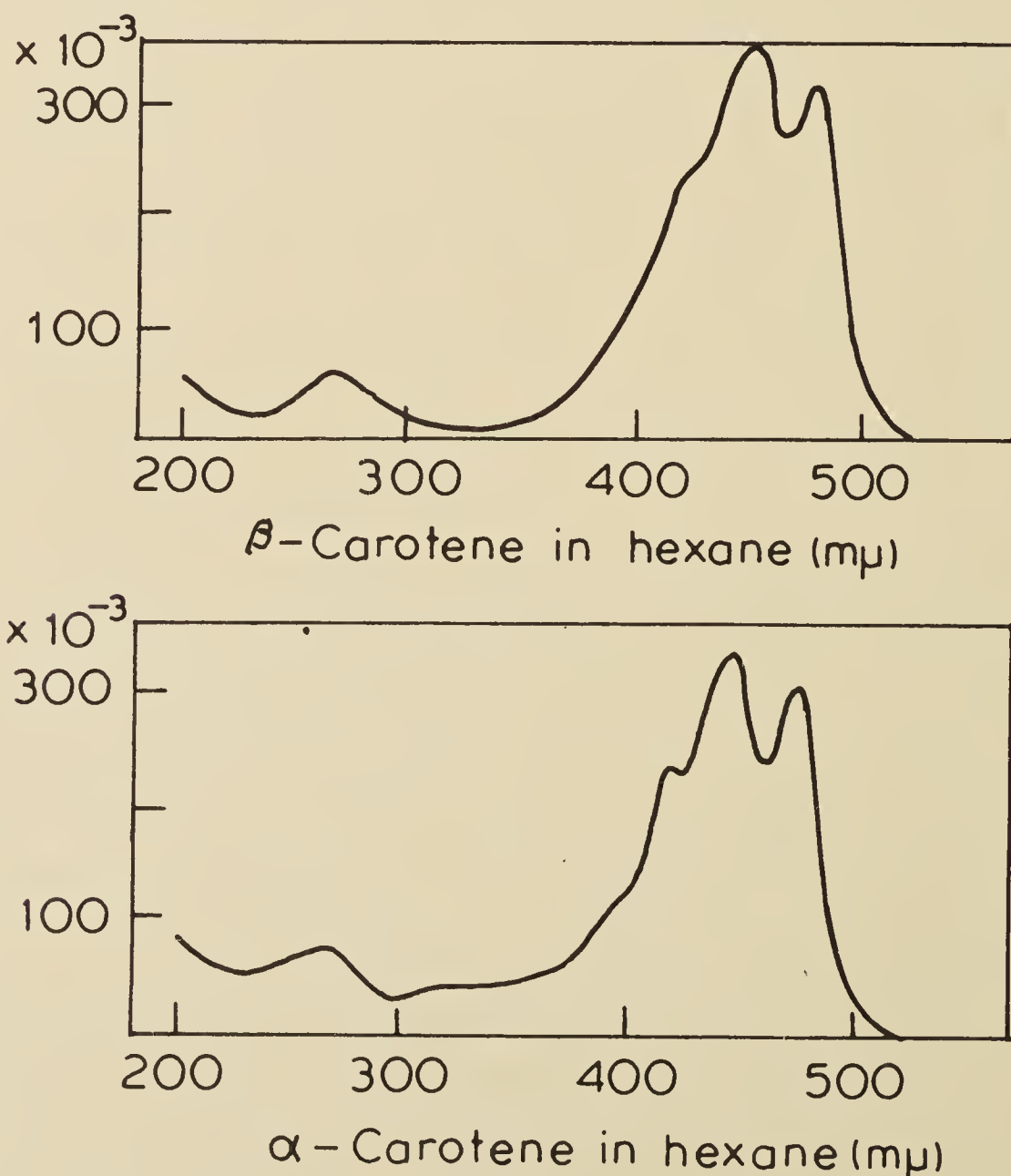


Figure 1. Light absorption curves.

are illustrated in figure 1 for the α - and β -forms of carotene. The two corresponding dihydroxy derivatives known as xanthophyll and zeaxanthin exhibit absorption curves closely resembling those of the respective carotenes. It should be mentioned that the precise positions of the maxima of absorption between 500 and 400 m μ are noticeably influenced by the choice of solvent for the observations. The actual positions of the maxima observed in hexane solution are for β -carotene 477, 450 and 425 m μ . The corresponding figures for xanthophyll in alcohol solution are 476, 447 and 420 m μ .

The relationship between the colour and the constitution of carotenoids have been extensively studied and empirical relations have been deduced. These will be found set out fully and discussed in the treatise of Karrer and Jucker. The absorption of light by the carotenoids in the visible region of the spectrum has been ascribed to electronic oscillations along the chain of conjugated double bonds. It can be predicted on this basis that the wavelengths and intensities of the maxima of absorption would increase with the number of conjugated ethylenic bonds in the molecule.

Of particular significance are the exceptions to the general rules regarding the form of the absorption curves which have been stated above. It will suffice to mention here three such cases, viz., rhodoxanthin (C₄₀H₅₀O₂), astaxanthin (C₄₀H₅₂O₄) and astacene (C₄₀H₄₈O₄). Their absorptions extend into the visible spectrum well beyond the usual limit of 500 m μ . Such extension is accompanied by noteworthy changes in the form of the absorption curve, the alternation of maxima and minima between 500 and 400 m μ becoming less pronounced or even completely disappearing. A single wide-band maximum is then observed in this region. These features are illustrated in figure 2. All three carotenoids whose absorption curves appear in the figure are derivatives of β -carotene. The changes noticed in their absorption curves are the result of the introduction of oxygen atoms, each replacing two hydrogen atoms in the closed rings which terminate the molecule. Astacene, for example, in which the wide-band maximum of absorption appears at 500 m μ may be described as tetraketo- β -carotene. That the spectroscopic behaviour of β -carotene is profoundly altered by this change in the chemical nature of the end groups in the molecule is not surprising.

Role of the carotenoids in vision: Visual pigments function by reason of their presence in the retina as well as their ability to absorb light in particular regions of the spectrum and to transfer the energy thus absorbed through the optic nerves to the cerebral centres of perception. By reason of the powerful absorption of light exhibited in the wavelength range between 400 and 500 m μ , carotenoid pigments are qualified to function as receptors of vision in this range. Studies on the visual perception of polarised light in the blue-violet sector of the spectrum and its relation to the structure of the fovea have been described in two earlier chapters. They pointed to the conclusion that a carotenoid is indeed the visual pigment which enables us to perceive light and colour in that range of the spectrum. We

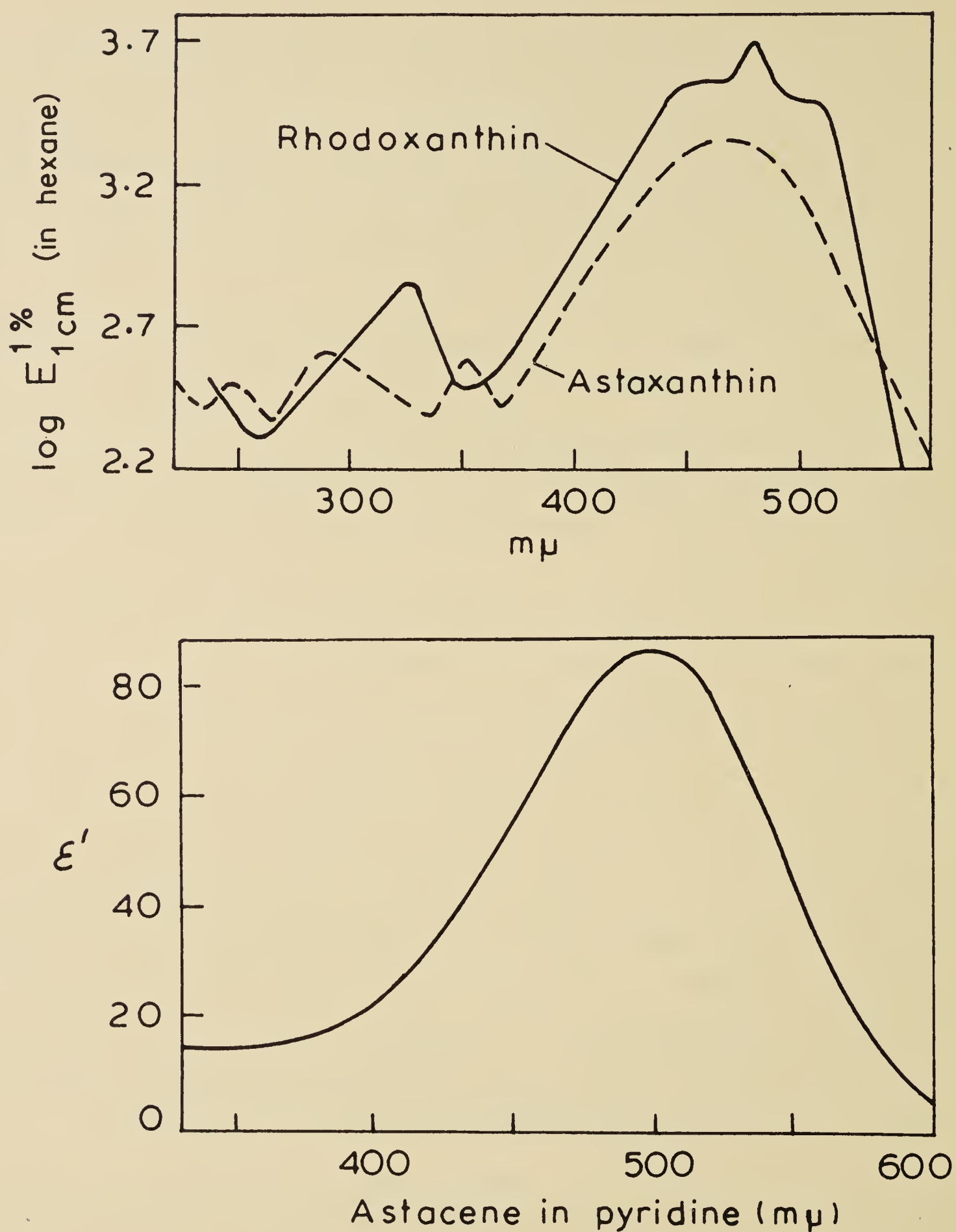


Figure 2. Light absorption curves.

shall revert to the same theme in the present chapter and describe further observations which confirm the stated finding and enable us to identify the pigment as xanthophyll.

The nature of the visual pigment functioning at low levels of illumination is another problem of great interest. It is a characteristic of vision at low levels of

brightness that we do not perceive the red end of the spectrum and in consequence, dim-light vision is practically confined to the spectral range between 400 and 600 $m\mu$. It has been shown in an earlier chapter that the ability to perceive feeble light with these spectral characteristics is not an exclusive feature of "rod vision", since it is exhibited just as perfectly by the cones in the retina. The ability to perceive dim light is indeed a general and fundamental aspect of human vision. From the spectral characteristics of dim-light, we may proceed to infer the features which we may expect to find exhibited by the light-absorption curve of the visual pigment which enables us to perceive dim light. This, in its turn, should assist us in identifying the pigment. Visual observations of the spectrum of dim light show that its maximum brightness is located at about 500 $m\mu$. What has been stated above and illustrated by the absorption curves reproduced in figure 2 indicates that the visual pigment functioning in dim light is a derivative of β -carotene in which the two groups at the ends of the molecule have both been modified suitably so as to give an absorption curve of the same general shape as that of astacene shown in figure 2. We shall consider this matter more fully as we proceed.

Colour and luminosity in the spectrum: Much knowledge regarding the visual perceptions of luminosity and colour emerges from very simple observations made with a long straight metallic filament stretched inside a tubular lamp and carrying an electric current as the source of light, and a replica-diffraction grating held before the eye as the dispersing apparatus. Altering the current through the filament with the aid of a rheostat, the light emission can be raised step by step from a dull red glow to the intense white light emitted by the filament at the highest temperature which it can carry. The results of the observations thus made will be described and discussed in a succeeding chapter. Here, we shall confine ourself to those features which have a bearing on the present topic, viz., the nature of the visual pigments which function in the blue-violet sector of the spectrum.

In the continuous spectrum of a moderately luminous source of white light, an observer can readily trace a progression of colour and luminosity as we pass along the spectrum. A feature which is immediately obvious is that the colour alters as we proceed quite slowly in some regions of the spectrum and quite rapidly in others. The transition from the blue to the green of the spectrum is one of the regions in which the changes are particularly rapid. 490 $m\mu$ is the wavelength at which the colour changes most rapidly and this can be fixed quite accurately by simple visual observations made with a wavelength spectrometer. Why such a rapid change occurs at this point in the spectrum is readily understood by reference to the absorption curves of the carotenes reproduced as figure 1 above and even better from that of xanthophyll exhibited in figure 3.

It will be seen that the strength of the absorption goes down steeply from a large value at 480 $m\mu$ to a relatively small value at 500 $m\mu$, the steepest fall being at 490 $m\mu$. Hence, if xanthophyll is the visual pigment which is principally

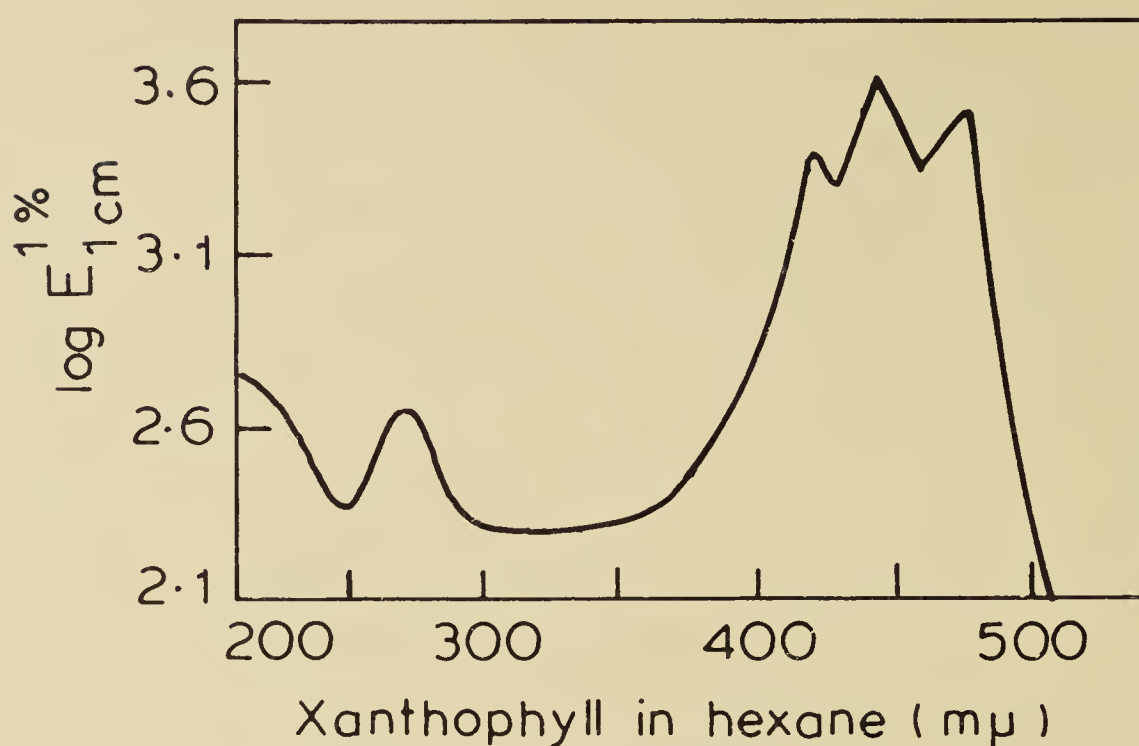


Figure 3. Light absorption curve.

functioning in the spectral range between 400 and 500 $m\mu$, the chromatic sensation excited by it would become weaker and tend to disappear as we proceed from 480 to 500 $m\mu$, while the chromatic sensation excited by the visual pigment functioning between 500 and 550 $m\mu$ would *pari passu* gain in strength. The rapid progression in colour and our ability to locate it precisely at 490 $m\mu$ are thus accounted for in a very satisfactory manner.

It is worthy of remark that the absorption by xanthophyll does not actually disappear at 500 $m\mu$ but continues to be sensible at 510 $m\mu$ beyond which it ceases to be significant. This is clear from the absorption-curves and it may also readily be verified by visual observation of the light-transmission through a solution of xanthophyll (mixed with a little zeaxanthin) obtained by the extraction of the yellow pigment of egg-yolk with hot acetone. With a sufficient absorption path, the cut-off of the spectrum appears at 510 μ accompanied by a sensible weakening up to 520 $m\mu$, beyond which there is perfect transparency. It follows from these circumstances that the contribution of xanthophyll to the colour perceived in the spectrum should extend well beyond 490 $m\mu$ where the change from blue to green is most rapid. Indeed, visual observation shows that the green of the spectrum has a distinct "blue edging" extending up to about 510 $m\mu$.

Further confirmation that xanthophyll is the visual pigment functioning between 400 and 500 $m\mu$ is forthcoming when a continuous spectrum of moderate intensity is surveyed through the eye-piece of a wavelength spectrometer. We notice three points in the spectrum at which impressive changes in its character are noticeable. The first is at 490 $m\mu$ as has already been mentioned and discussed. The second is at 465 $m\mu$ and the third is at 435 $m\mu$. At 465 $m\mu$, there is a marked change of colour and at 435 $m\mu$ there is a marked change of intensity. The three zones in the spectrum thus marked off are also those into which the spectrum is divided by the three peaks of absorption depicted in figure 3. The

observed differences in colour and intensity between the three zones are explicable in terms of the large differences in the absorptive power of xanthophyll in those regions of the spectrum, when the other circumstances of the case are also taken into account.

Perception of polarisation: Still another confirmation that xanthophyll is the visual pigment functioning in the 400 to 500 m μ range of spectrum is furnished by the effects noticed when this region of the spectrum is surveyed from point to point by an observer holding a polaroid in front of his eye and swinging it to and fro in its own plane through 90°. A well-dispersed continuous spectrum exhibiting an adequate intensity over its entire range is essential for such observations. When these requirements are secured, the following features come to light:

(a) The phenomenon of the brushes described in an earlier chapter continues to be noticeable, though much enfeebled, in the region of wavelengths between 500 m μ and 520 m μ . It disappears completely at wavelengths greater than 520 m μ .

(b) The brushes can be seen over the entire range of the spectrum from 500 m μ to the extreme violet end.

(c) Their clearness depends much on the luminosity of the spectrum in the region under observation. There are also indications that it exhibits variations, being greatest in certain regions and distinctly less in others.

Presence of xanthophyll in the retina: The observational evidence set forth above justifies the inference that xanthophyll is present in the living retina and that it functions as a visual pigment. But it is not superfluous to add that its presence is also attested by independent evidence. Xanthophyll may be identified and indeed has been identified in the past as the material responsible for the yellow pigmentation of the macular region of the retina. In a later chapter, we shall also present direct observational evidence for the presence diffused over an extensive area of the retina of a pigment which absorbs light in the blue-violet sector of the spectrum and enables us to perceive light and colour in that sector.

Some remarks regarding the question whether β -carotene is or can be the visual pigment functioning in bright light may be made here. There are weighty reasons for excluding that possibility. Blue-blindness is a very rare condition and this indicates that the visual pigment necessary for the perception of the blue in the spectrum is present in abundant measure with little possibility of its running short. Xanthophyll is not a vitamin precursor and not being needed for other purposes can find its way into the retina through the blood stream to the extent needed and be replenished whenever necessary. If β -carotene were present in the retina along with xanthophyll, it would function as a visual pigment in much the same way. The differences between the form of their absorption spectra might perhaps lead to detectable differences in their functioning. But this possibility

scarcely needs consideration, since β -carotene has other physiological functions to perform which make it most unlikely that it is present in unmodified form in the retina to the same extent as xanthophyll.

Perception of dim light: It is indisputable that there is present in the retina a material that enables us to perceive dim light in the spectral range between 400 and 600 $m\mu$ and which has its maximum luminous efficiency at or near 500 $m\mu$. But the idea which has so far prevailed that this material is a constituent part of the structure of the "rods" and that it functions only in "rod-vision" is definitely false. As has been shown in earlier chapters, dim light can be perceived also by the cones in the retina, including especially those in the foveal region where there are only cones and no rods. It follows that the visual pigment is spread and distributed through the substance of the retina in such manner as to permit of rods and cones alike functioning in dim light. Studies which base themselves on the extraction of material from the rod-structures by chemical or mechanical methods are therefore not really relevant to the problem of determining the nature of the visual pigment.

The physiology of vision is concerned with the functioning of the retina in the living state. It follows that we have to rely principally on the actual facts of visual experience and to base their interpretation on other facts and on well-established principles. The basis for all considerations regarding the nature of the visual pigment is, *firstly* that its spectral sensitivity extends over the entire visible spectrum up to 600 $m\mu$, but that it does not extend further towards the red end and, *secondly* that the maximum of its luminous efficiency appears at about 500 $m\mu$. These facts by themselves make it practically certain that the pigment is a carotenoid. Indeed, if we look through the 30 light-absorption curves reproduced at the end of the treatise by Karrer and Jucker, we do not find a single instance in which the strength of the absorption at any wavelength greater than 500 $m\mu$ exceeds that at 500 $m\mu$. Nor do we find a single instance in which the authors of that treatise thought it necessary to extend the scale of wavelengths beyond 600 $m\mu$. The reason for this is that in nearly all cases, the absorption ceases to be significant beyond 550 $m\mu$. In a majority of cases, also, the absorption reaches its maximum at or near a wavelength of 500 $m\mu$. As has already been remarked on an earlier page, the wavelengths and intensities of the maxima in the absorption spectra of both natural and synthetic polyenes increase with the number of conjugated ethylenic bonds. The absorption spectra are therefore an indication of the number of such bonds contained in the molecule.

In view of what has been stated above, it may justifiably be inferred that the visual pigment functioning in dim-light vision is a carotenoid having the same number of ethylenic bonds as β -carotene. We shall also be justified in inferring that it is a derivative of β -carotene in which the two groups appearing at the ends of each molecule have been so modified as to render its absorption spectrum generally similar to that of astacene represented above in figure 2.

Carotenoid chemistry makes extensive use of oxidative and reductive processes in which suitable reagents are employed. Numerous examples of this will be found set out in the chapter on the synthesis of carotenoids in the treatise of Karrer and Jucker. There is present in the retina a substance, viz., oxyhemoglobin, which can transfer its oxygen content to other materials, being itself reduced to hemoglobin in the process. One may, therefore, venture to put forward the suggestion that the transformation of β -carotene to a derivative having an altered spectroscopic behaviour is effected through such oxidation. The pigment thus formed could scarcely be expected to be light-fast. In other words, it would break up and result in other substances being formed when exposed to strong light. Its formation can therefore take place only in dim light or in complete darkness. These are, in fact, the characteristic features of the visual pigment functioning in dim light.

Night-blindness and its origin: The β -carotene that enters the human body by way of the food-stuffs consumed has to play a dual role. It has, in the first place, to function as the parent of vitamin A, and in the second place to provide the material needed for vision in dim light. As the supply of β -carotene is limited by the quantity and by the quality of the food-stuffs consumed, it is scarcely surprising that in certain circumstances it may prove insufficient to meet the requirements. As is well-known, vitamin A is stored up in the liver and also elsewhere in the human body and that the reserves can be drawn upon when necessary. A deficiency in the carotenic content of food would therefore in the first instance result in an inadequate replenishment of the visual pigment which is destroyed by exposure to bright light. This would produce a condition of partial or complete night-blindness, which can, of course, be set right by an increased consumption of food-stuffs containing β -carotene. Alternatively, the addition to the food of material with a large content of vitamin A would serve the same purpose. For, this would reduce the major demands for a supply of β -carotene and enable more to be available for vision. It is even possible that the transformation of β -carotene to vitamin A in the human body is a reversible process, and that doses of vitamin A may remedy the deficiency in the carotenoid input needed for vision.

The new physiology of vision— Chapter XII. Chromatic sensations at high luminosities

SIR C V RAMAN

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The chromatic sensations excited by light and the closely related topic of the progression of luminosity and colour in a well-dispersed spectrum play a highly important role in the physiology of vision. It emerged from the studies described in the preceding chapters that the sensations of luminosity and colour are so closely interrelated that they have of necessity to be considered together. At the lowest levels of illumination, they are both extremely feeble. They both gain strength as the flux of light reaching the retinae of our eyes increases. These features naturally also manifest themselves when the light from a source of continuous radiation is dispersed into a spectrum and this is viewed by an observer. There is also a notable difference in the extent of the spectrum exhibited at the levels of illumination which we have referred to as dim light and as bright light respectively. These differences are attributable to the visual pigments which are present in the retina and function at the two levels being altogether different in their spectroscopic behaviours.

It is obviously of importance to carry the studies forward to levels of illumination higher than those which are normally made use of in vision. The results of such study may well be expected to throw fresh light on the nature of the visual processes. This indeed proves to be the case. The observations presently to be described lend impressive support to the findings set out in the two preceding chapters regarding the nature and functioning of the visual pigments.

Technique of study: A simple and yet highly effective method has been adopted by the author for investigations in the field outlined above. It consists in the use of a linear source of light and the observation of its first-order diffraction spectrum through a replica grating held by the observer before his eye. The grating employed had 6000 rulings per cm and its first-order spectrum exhibits a dispersion and resolution more than adequate for the purpose in view. A convenient source of light is a tubular lamp along the axis of which is stretched a closely coiled tungsten filament 20 cm in length. The current carried by the filament can be varied with the aid of a rheostat so that the radiation emitted by it

can be stepped up from a dull red glow to a brilliant white light. The spectrum is viewed by the observer who places himself at a suitable distance from the light source. This can be varied from the largest distance permitted by the dimensions of the laboratory down to quite small values. The brightness of the spectrum imaged on the retina is thereby enhanced roughly in inverse proportion to the distance. Even when the observer is 10 m away from the light source, the length of the glowing filament enables the width of the spectrum to be sufficient for its characters to be clearly perceived. The increase in luminosity which results from stepping up the heating current is very large for all parts of the spectrum. In particular, the blue-violet sector of the spectrum which is not observable when the tungsten wire emits a feeble red glow gains enormously in intensity when the temperature is raised and a brilliant white light is emitted. But, nevertheless, it continues to be the least luminous part of the spectrum. By the observer moving nearer to the source as also by raising the temperature of the filament, the observed luminosity of the spectrum can be raised from a barely perceptible value to one of considerable brilliance.

Still higher levels of brightness can be attained by using the special type of tungsten filament lamp which is commercially available and is employed for cinematographic projections. In these lamps, the source of light is a coiled-coll of fine tungsten wire placed inside a glass bulb which has a flattened shape. The rear part of the bulb is silvered externally and it acts as a reflecting mirror and brings the emitted light to a focus just outside the bulb. A slit cut in a metal plate and held at the focus allows the light to emerge and functions as a linear source of great intensity. The first-order diffraction spectrum of the illuminated slit can be viewed by the observer from any desired distance.

The results of the study: In the two preceding chapters, the parts of the spectrum between 7000 and 5000 Å and between 5000 and 4000 Å in wavelength were separately dealt with and discussed. This bifurcation of the spectrum was justified by the fact that the visual pigments functioning in the two cases are altogether different. It need not therefore surprise us to find that the effect of high luminosities on the visual sensations experienced are of a totally different nature in the two cases. Accordingly in the present chapter, we shall consider only the spectral region between 5000 and 7000 Å. The part of the spectrum between 4000 and 5000 Å will be discussed in the chapter immediately following. As already stated, the techniques of observation enable us to cover a great range of luminosities in the spectrum, from the weakest observable to the strongest attainable. It is convenient therefore to describe the observed effects stage by stage in the same order.

First stage: With the tubular lamp emitting a dim red glow and the observer far away from it, the spectrum is at its weakest. The blue-violet sector is entirely absent and the red part of the spectrum also lies outside the range of visual

perception. What is then actually observed in the region between 500 and 600 m μ . Despite the dimness of the spectrum, the greenish hue of the part that is visible is recognisable. If now the observer comes nearer the lamp, the red of the spectrum reappears and progressively gains in strength.

Second stage: The character of the spectrum is now totally different from that observed in the first stage. The red sector of the spectrum appears in full strength, while the green has gained both in colour and in brightness. These colours are fully saturated and are strikingly contrasted. The transition from the red to the green is fairly rapid and can be located in the spectrum with considerable accuracy. But where the two colours come closest to each other, the progressive change in hue from one to the other with the yellow between them can be readily perceived.

Third stage: Further conspicuous alterations in the character of the spectrum are observed when we pass from the second to the third stage. The band of yellow which separates the red from the green is now both broader and brighter. With increasing luminosity, the yellow becomes much the brightest part of the spectrum. The green and the red sectors also exhibit an altered appearance. The changes they exhibit are best described as the result of a progressively increasing superposition of the yellow sensation on the green and on the red sensations. Such superposition would result in altering the perceived colour from green to a greenish-yellow and from red to an orange. These changes spread outwards from the yellow part of the spectrum on both sides to a greater and greater extent with increasing luminosity.

Fourth stage: At this stage, the yellow strip in the spectrum attains great brilliance and appears as a band which is far brighter than the regions on either side of it. These latter exhibit the features already described for the third stage.

Fifth stage: At this stage the yellow of the spectrum becomes extremely brilliant and also spreads out to include within itself both the green and the orange tracts of the spectrum. It has then the appearance of an intensely luminous band of a yellowish-white colour with strips of blue and of red of relatively low intensity extending outwards from it on the two sides.

It should be mentioned that the third, fourth and fifth stages can all be quickly traversed and their characteristics noted by an observer with the slit and projection lamp described earlier, merely by varying his distance from the slit or alternatively by varying the electric current through the lamp. These observations establish in a very striking fashion that both in normal circumstances and at the higher levels of illumination, the yellow of the spectrum is the dominant visual sensation and transcends all the other parts of the spectrum in its impact on the centres of perception. Likewise, the visual pigment which enables the perception of the yellow region of the spectrum is clearly the most important of them all.

The new physiology of vision—Chapter XIII. Blue, indigo and violet in the spectrum

SIR C V RAMAN

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The studies of colour in the spectral range between 5000 and 4000 Å at various levels of brightness made by the author and presently to be described have yielded results of great interest. It is found that the basic sensation excited by radiations falling anywhere within this spectral range is that of violet. In other words, light everywhere in this spectral region exhibits a violet colour if its brightness does not much exceed the minimum needed for the perception of sensible colour. As the intensity is increased, the violet passes over at a fairly definite level of brightness to a sensation which may aptly and correctly be described as indigo. At a still higher level of brightness, the colour changes over to a bright blue colour. These remarkable results have been established using several different techniques of observation which will be set out fully as we proceed. All the three colours, viz., blue, indigo and violet may be perceived following each other in the order stated in the spectrum of continuous radiation if this has the appropriate intensities.

Another result of great interest which has emerged from the present investigation is that in the spectrum of continuous radiation, three maxima of luminosity separated by regions of lower brightness may be observed visually. The positions of these maxima have been located at 470, 435 and 410 mμ. These maxima of visual brightness appear in the same positions as the known maxima of absorptive strength in the spectrum of the visual pigment xanthophyll functioning in this region of the spectrum.

Techniques of observation: One of the simplest methods for the study of the colour-luminosity relationship in the spectrum is visual observation with the aid of a replica diffraction grating of the light from the linear source furnished by an opening between the wooden shutters of a darkened room. The observer holds the grating before his eye and scans the diffraction spectra seen in his field of view. The best time for such observations is in the early morning hours; the window should face eastwards, so that a strip of the brilliantly luminous sky in the vicinity of the sun is seen through the opening between the shutters. At that hour, owing to the rays of the sun having traversed a great depth of atmosphere, light having the shortest wavelengths is much attenuated. Examination with a pocket

spectroscope shows a rapid falling off in brightness between 450 and 430 $m\mu$ and no observable intensity at smaller wavelengths. But the observations can also be made at other times when the spectrum extends to lower wavelengths.

The width of the opening and the distance of the observer from it may both be adjusted so that the diffraction spectra have adequate intensity and at the same time exhibit adequate resolution and dispersion. A further device which is extremely useful is for the observer to place immediately before the diffraction grating, a colour filter of gelatine film dyed with "disulphine blue". (The preparation of such filters will be described fully in a later chapter.) This filter effectively cuts off the red, orange and yellow of the spectrum and allows only wavelengths less than 560 $m\mu$ to reach the eye of the observer. Apart from making it easier to observe the colours in the rest of the spectrum without dazzle or interference, the cut-off of wavelengths greater than 560 $m\mu$ prevents the overlap of the diffraction spectra of higher orders with each other. It then becomes possible to study the colours exhibited between 500 and 430 $m\mu$ not only in the first-order diffraction spectrum but also in the second-order and third-order spectra. These are, of course, of much lower intensities.

Results of the study: With the arrangements described above, it is found that the appearance of the spectrum in the region following the green sector is altogether different in the first, second and third-order diffraction spectra. The intensity of the spectra can be controlled by varying the width of the opening between the shutters, the observer retaining his position at a convenient distance from it. It is best to adjust the luminosity so that the third-order spectrum is just sufficiently bright for it to be clearly perceived. The first-order spectrum then exhibits a blue colour between 490 and 460 $m\mu$ and an indigo between 460 and 430 $m\mu$. In the second-order spectrum, on the other hand, the blue is unobservable and the region between 490 and 430 $m\mu$ exhibits the indigo colour. The third-order spectrum exhibits a violet hue over the entire region.

Very similar results are obtained using the artificial light source provided by a tubular lamp with a tungsten filament stretched along its axis and heated by an electric current. The observer views the diffraction spectra of different orders of this light source with a replica grating and the "disulphine blue" colour filter held before his eye. The luminosity of the spectrum may be quickly and rapidly controlled by moving the slide on the rheostat which varies the current heating the tungsten filament. The same result can also be achieved by the observer moving away from or towards the lamp. The entire sequence of changes in the colour exhibited over the whole spectral change can thus be quickly and conveniently followed.

Still another procedure which enables the colour-luminosity relationships to be studied in a quantitative fashion is to observe the spectrum of the continuous radiation of a tungsten-filament lamp through a wavelength spectrometer. A coiled-coil filament lamp giving a brilliant white light of the type used in

projection work is very suitable for such observations. A sheet of opal glass placed immediately in front of the slit of the spectrometer helps to diffuse the light entering the instrument and enables its full aperture to be utilised. By moving the light source away from the opal-glass sheet, the level of illumination in the spectrum under observation can be varied over a great range in a calculable fashion. The observer can then view the spectrum in the focal plane of the instrument through an eyepiece and follow the changes in the colour sequence as the lamp is moved away from the opal-glass sheet. It will be noticed that the blue part of the spectrum progressively contracts, being replaced by the indigo and finally by the violet colour which is the basic hue of the spectrum throughout the wavelength range between 500 and 400 m μ .

Observations with sunlight: If sunlight is admitted into a darkened room through a narrow slit and the emerging pencil of rays after traversing a dense flint-glass prism of 60° angle is received on a white screen placed at a suitable distance, one observes the solar spectrum after the manner of Newton. The differences in colour between the blue, indigo and violet regions in the spectrum then observed are so very striking that one can only wonder why later writers have not accepted Newton's description of the colours of the spectrum. Had they taken the trouble to repeat Newton's experiments making use of the high luminosities made possible by sunlight, they would have realised that his description was entirely accurate. Incidentally, it should be remarked that in the spectrum seen under these conditions, the maximum visual brightness appears in the yellow region and not in the greenish-yellow.

The spectrum of sunlight can also be exhibited in a spectacular fashion with the aid of a diffraction grating having a large ruled area. Sunlight reflected by a heliostat enters a darkened room through an aperture of area 10 × 5 cm and after the beam has traversed a distance of two metres, it is incident on a replica diffraction grating with a ruled area also of the same size (10 × 5 cm). The first-order diffraction spectrum resulting from the passage of the light through the grating is received on a white screen 8 m away from the grating. It is then seen as a brilliant band of colour stretching over a length of 150 cm. In the region of shorter wavelengths, three regions are noticed of which the colours are quite different and readily distinguishable from each other, viz., blue, indigo and violet.

Instead of allowing the spectrum to diverge from the grating and fall on a distant screen, a more satisfactory arrangement is to use a telescopic objective of sufficient aperture (15 cm) and of sufficiently great focal length (400 cm). The first-order diffraction spectrum is brought to a focus by the objective and the intensity and the definition of the spectrum are thereby greatly improved. The spectrum is received on a ground-glass screen and is viewed by the observer. By covering up the ruled area of the diffraction grating, its aperture may be progressively reduced from 10 cm down to a mm and the brightness of the spectrum is thereby proportionately reduced. Remarkable changes are then

noticed in its colour. When the full aperture of the grating is functioning, the blue region covers the greater part of the spectrum between 500 and 400 $m\mu$, the indigo and the violet occupying only small parts near the end. As the luminosity is diminished, the blue progressively contracts and ultimately disappears, being replaced by the indigo and then by the violet. In the final stages, the entire spectrum after the green exhibits a violet hue.

Colours in line spectra: The light emitted by the radiating atoms is localised in their spectra and appears as sharply defined lines. When these lines are observed visually through a dispersing apparatus, they would generally appear to be of much greater intensity than any continuous spectrum accompanying them. The colour-luminosity relationship would then make itself felt as an observable difference between the colour of the spectral line and of the continuous spectrum on either side of it. Such a difference is conspicuously exhibited by the λ 4358 line in the spectrum of the mercury vapour lamp when there is an accompanying continuous spectrum. It appears of a bright blue colour, while the continuous spectrum on either side exhibits a violet hue resembling that of the λ 4046 radiation.

Spectral lines of low intensity in the region between 500 and 400 $m\mu$ may exhibit colours different from those normally to be expected in that region. This phenomenon may be observed in the spectrum of a sodium vapour lamp soon after it is started, when feeble emission lines of gas atoms other than sodium are also present. Lines appear which exhibit a violet hue instead of the blue colour to be expected from their positions relatively to the stronger lines.

Origin of the three colours: The foregoing recital of the actual facts of observation leaves us with some questions which need to be answered. Why are three colours readily distinguishable from each other exhibited in the spectral range under consideration? Why do the colours alter when the level of brightness is varied? Some light is thrown on the issues here raised by a few further observations presently to be described.

The absorption spectrum of xanthophyll has already been described in detail in an earlier chapter, but it may be briefly recalled here. The absorption increases from zero at 520 $m\mu$ to a substantial value at 500 $m\mu$. It then rises steeply and exhibits a pronounced maximum at 476 $m\mu$. It then dips down to a minimum, beyond which it recovers and exhibits a second and even more pronounced maximum at 447 $m\mu$. Thereafter, there is a fall which is however interrupted by the appearance of a third but less pronounced maximum at 420 $m\mu$. There is then a continuously diminishing absorption as we pass from the visible to the ultraviolet region.

These various features show a close relationship to the visually perceived features in the same range of the spectrum. It has already been remarked that the first steep rise in absorption around 490 $m\mu$ occurs precisely where the observed

colour of the spectrum changes rapidly from green to blue. In the present study, a further remarkable parallelism has come to light. This is the appearance of bands of higher luminosity in the spectrum which coincide in their respective positions with the absorption maxima of xanthophyll. To observe these bands, the same technique is employed as that described earlier for the studies of colour in this region. The observer views the first-order diffraction spectrum of a luminous tungsten filament produced by a grating held before his eye. The bands commence with a noticeable fall in luminosity in the spectrum where the green ends and the blue begins. Following this, a bright band with a maximum of intensity at $470\text{ m}\mu$ is readily recognisable. A further drop in luminosity is followed by a recovery and a second maximum of brightness at $435\text{ m}\mu$ is noticed. Beyond this again, there is a further drop in intensity followed by a recovery in which the third and last maximum at $410\text{ m}\mu$ is discernible. The first maximum at $470\text{ m}\mu$ falls in the blue region, the second maximum at $435\text{ m}\mu$ in the indigo and the third maximum at $410\text{ m}\mu$ appears in the violet.

These facts of observation suggest that the reason why three distinct colours manifest themselves to our visual perceptions in the spectral range between 500 and $400\text{ m}\mu$ is just that the absorption spectrum of xanthophyll has three maxima in this spectral range, these three maxima covering the regions in which the three colours respectively appear. This, however, leaves unanswered the question why the perceived colours alter with the level of brightness in the spectrum. But such alterations are not altogether unexpected. In the preceding chapter, we have noticed that the colour sensations which are experienced in the spectral range between 5000 and 6000 \AA are strongly influenced by an increase in the level of luminosity. It need not therefore surprise us to find that in the adjoining spectral region between 4000 and 5000 \AA , changes in the level of luminosity also produce striking changes in the colour sensations. That they are of a different nature need not also surprise us. For, in the former case, the visual pigments which function are heme and its derivatives which are biological products of human metabolism whereas in the latter, it is the carotenoid pigment xanthophyll, a plant material which has found its way into the human body by way of food products consumed. In the two cases, we are dealing with the pigments which differ profoundly in their chemical structure as also in their spectroscopic behaviour.

The new physiology of vision—Chapter XIV. The red end of the spectrum

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In the present chapter, we shall concern ourselves with the visual sensations excited by light of wavelengths between $579\text{ m}\mu$ and the long-wave limit of the visible spectrum. Some of the features of this region which are evident to simple inspection may first be mentioned. The yellow at $579\text{ m}\mu$ is followed by the region in which the hue passes from yellow to red through various intermediate colours usually termed as orange. This region extends up to about $630\text{ m}\mu$ and it is highly luminous. From 630 to $660\text{ m}\mu$ the colour is red, but the luminosity of the spectrum falls off. This is followed by a region in which there is a further rapid diminution in brightness. Beyond $690\text{ m}\mu$, the spectrum becomes excessively feeble.

It is a remarkable and indeed significant fact that it is not possible by observation to fix a definite wavelength as that beyond which the red of the spectrum ceases to be observable. It is found, for example, that an observer who views the highly luminous part of the sky in the vicinity of the sun through a pocket spectroscope would be inclined to place the limit at $700\text{ m}\mu$. But if, on the other hand, he directs the same instrument towards the blue sky far away from the sun, he would find that nothing can be seen of the spectrum beyond $670\text{ m}\mu$. Likewise, if inside a room illuminated by diffuse daylight, the same instrument is directed towards a whitewashed wall, he would decide that the spectrum terminates at $650\text{ m}\mu$, but also exhibits a rapid fall of intensity between 630 and $650\text{ m}\mu$.

The experiences set forth above become intelligible when we consider the spectroscopic behaviour of the visual pigments functioning in the long-wave region of the spectrum. The data regarding their properties were already set out in an earlier chapter, but are here reproduced again as figure 1 covering the spectral range between 500 and $800\text{ m}\mu$. The graphs have been copied from the chart appearing at the end of the volume by Lemberg and Legge entitled *Hematin Compounds* (Interscience, New York and London, 1949). The most conspicuous feature noticeable in the figure is the rapid diminution in the molecular extinction coefficient of all the three pigments which exhibits itself as we proceed towards longer wavelengths. But as between the three, there are noteworthy differences.

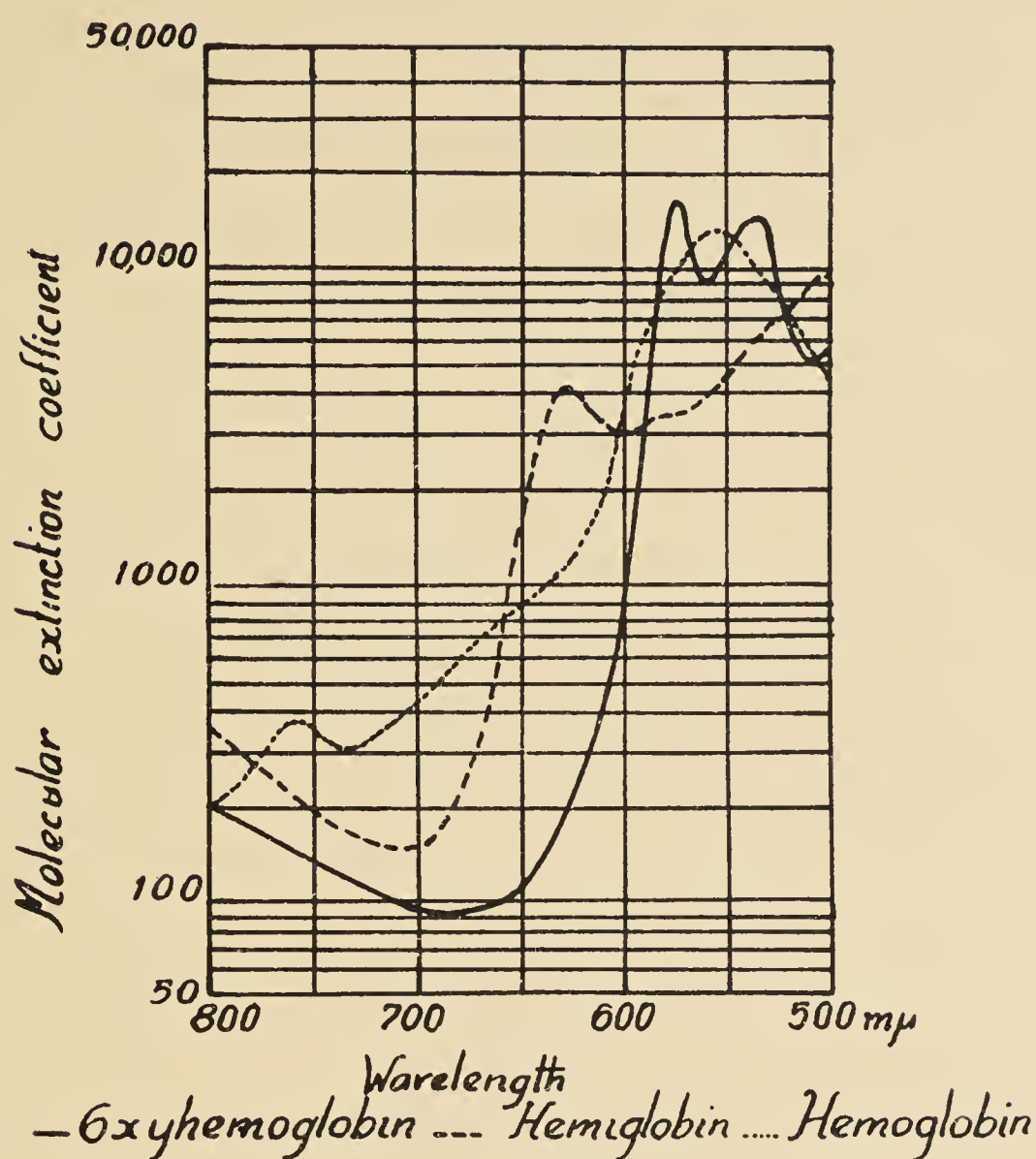


Figure 1. Light absorption curves.

The ferrous form of the heme pigment exhibits a wide-band maximum located at about 560 mμ, its absorption falling off to a small fraction of that value for wavelengths greater than 650 mμ. The oxygenated form of the heme pigment exhibits a sharply defined peak at 579 mμ coinciding with the yellow of the spectrum; following this, there is an extremely rapid fall of the molecular extinction coefficient, its value becoming quite small at 600 mμ and entirely negligible at 650 mμ. The ferric form of the heme pigment has high values of the extinction coefficient in the spectral range between 600 mμ and 630 mμ, in other words, in the range of wavelengths in which the perceived colour exhibits the transition from red to orange. There is a well-defined maximum at 630 mμ. Beyond 630 mμ the extinction coefficient drops off very rapidly and becomes quite negligible at 700 mμ.

What has been stated above enables us to arrive at certain conclusions. Firstly, it is the ferric form of the heme pigment which principally enables us to perceive the orange and the red sectors of the visible spectrum. The properties of that pigment also explain why the visible spectrum in the wavelength range between 600 and 630 mμ exhibits a high luminosity, why that luminosity diminishes rapidly in the range between 630 and 660 mμ, why the red of the spectrum

becomes extremely weak in the spectral range between 660 and 700 $m\mu$ and why except at very high levels of illumination it ceases to be observable beyond 700 $m\mu$. Further, since the observable extension of the spectrum depends on the level of illumination, we may expect that the entire red of the spectrum would disappear and cease to be visible and would be followed by the orange sector as well, when that level is lowered sufficiently.

The Purkinje phenomenon: The disappearance from sight of the red region in the spectrum has, in the past, been believed to be a characteristic feature of vision in dim light and to require the adaptation of the eye to low levels of illumination. That these beliefs are erroneous will be evident from what has been stated above. Actually, the Purkinje phenomenon arises by reason of the spectroscopic properties of the visual pigments which function in bright light and it is observed in circumstances that do not require the adaptation of the observer's vision to dim light. These inferences have been confirmed and firmly established by the author's studies using several different techniques which will presently be described. The essence of the matter is that the disappearance of red light from the visible spectrum is a progressive phenomenon. It commences at quite high levels of illumination for the longest waves and proceeds towards shorter wavelengths with diminishing illumination, till finally the entire spectrum of wavelengths greater than 600 $m\mu$ drops out of sight.

A simple and convenient procedure for demonstrating the real nature of the Purkinje phenomenon is to examine the spectrum of skylight visually using a pocket spectroscope. The most suitable time for such observations is either in the morning just before sunrise or in the evening just after sunset, when the illumination of the sky by the sun's rays traversing the higher levels of the atmosphere is sufficiently strong to enable the spectrum of every part of the sky to be seen through such an instrument clearly and without the least difficulty. Observations made under these conditions belong to the category of vision in bright light. Indeed, the spectrum itself exhibits features which distinguish it sharply from the spectrum of dim light. But it differs from the spectrum of skylight as seen at other hours by reason of the extreme weakness or total absence of the parts of the spectrum of which the wavelengths exceed 600 $m\mu$.

The character of the spectrum as actually observed in the conditions stated above is determined by the luminosity of the part of the sky under view. Naturally, therefore, it varies with the direction of observation and alters as the sun comes up towards the horizon or goes down below it. The general sequence of the changes observed is however the same in all cases. Indeed, except in the areas close to the position of the sun, we observe the same effects almost simultaneously in all parts of the sky. In the first stage, there is a progressive shortening of the length of the spectrum, wavelengths greater than about 650 $m\mu$ ceasing to be visible. In the second stage, there is a progressive fall in the brightness of the spectrum between 600 and 650 $m\mu$ as compared with the spectrum between 500 and 600 $m\mu$. In the

final stage, the region of the spectrum beyond $600\text{ m}\mu$ passes out of sight, while the region between 500 and $600\text{ m}\mu$ continues to be conspicuously visible. The maximum brightness in the latter region appears at about $550\text{ m}\mu$; its colour is a bright green and quite different from the colour observable in the region of wavelengths less than $500\text{ m}\mu$. The latter regions are also much less luminous than the spectrum between 500 and $600\text{ m}\mu$. It is clear from these facts that the Purkinje phenomenon falls within the category of vision in bright light and is in no way related to the characteristics of vision in dim light.

That red light ceases to be visible at levels of illumination higher than those falling within the range of dim-light vision can be further demonstrated in the following simple fashion. A large plastic sheet of red colour with faces exhibiting a smooth polish is set up facing the observer at a distance of a few metres from him. Alongside of it and at the same distance from the observer, is placed a Snellen test-chart with printed rows of letters of the kind used by ophthalmologists. The illumination of the red plastic sheet and of the test-chart is controlled by varying the opening of a large iris-diaphragm through which skylight enters the otherwise darkened room. It is then found that the red screen becomes darker and finally turns black when the iris is closed down sufficiently, while on the other hand the printed types of the Snellen chart continue to be visible and can be read from a distance without difficulty. Spectroscopic examination shows that the light diffused by the plastic sheet appears in the spectral range between 580 and $700\text{ m}\mu$, while the rest of the spectrum is completely absorbed by the material of the screen. The Purkinje phenomenon thus extends over the entire range of wavelengths between the yellow and the extreme red of the spectrum.

Other methods of observation: The conclusion thus reached is that in the familiar Newtonian sequence of colours exhibited by a continuous spectrum, the hues ranging from yellow to the deepest red disappear in the reverse order as the illumination reaching the eye is progressively reduced. It is evidently desirable that this result which is of fundamental importance in the physiology of vision is demonstrated with artificial light sources having a continuous spectrum and a controlled intensity under laboratory conditions. This can easily be arranged. A convenient technique is to use as the source of light a 100-watt tungsten filament-lamp with a frosted bulb. The spectrum seen when the pocket spectroscope is held close to the bulb is, of course, extremely brilliant. The yellow region is its most conspicuous feature and the orange and red which follow it can be seen extending up to $700\text{ m}\mu$. To obtain a controlled and progressive reduction of brightness, a useful device is to hold a sheet of opal glass 2.5 mm thick between the lamp and the observer. The spectrum of the light emerging through the sheet is viewed with the pocket spectroscope held behind it. The reduction of luminosity resulting from the insertion of the sheet of opal glass between the lamp and the observer is very striking. Indeed, the entire sequence of changes in the spectrum from one exhibiting the features characteristic of high illumination to one in which all

wavelengths greater than $600\text{ m}\mu$ have disappeared from sight can be followed merely by the observer holding the opal glass sheet and the spectroscope and moving away from the lamp to the further end of the laboratory a few metres away. To observe the same sequence without the aid of the opal glass sheet would require a movement which is far larger. Incidentally, it may be mentioned that the disappearance of the red end of the spectrum is well exhibited by distant street lights when they are viewed through a pocket spectroscope.

Another technique by which the real nature and characteristics of the Purkinje phenomenon can be effectively displayed requires the use of a straight metallic filament stretched along the axis of a tubular lamp and heated by an electric current. At a convenient distance from the lamp, the observer holds a replica diffraction grating before his eye and views the first-order diffraction spectrum of the luminous filament. When this is glowing at a white heat, the spectrum exhibits its greatest extension both towards the violet and towards the red; the spectrum is seen extending to $700\text{ m}\mu$ or even a little beyond. A reduction of the heating current has the effect of weakening the entire spectrum, especially the region of shorter wavelengths and ultimately of extinguishing the latter. But the green sector of the spectrum continues to be visible, and the noteworthy feature is the progressive shortening of the red sector of the spectrum. As the heating current is reduced, the red in the spectrum then becomes weaker and weaker relatively to the green region and finally disappears, while the green continues to be visible. This, in fact, is the Purkinje phenomenon and proves that it is a progressive diminution in the visibility of the spectrum which commences at $700\text{ m}\mu$ and ends up with the complete extinction of the spectrum beyond $600\text{ m}\mu$.

Observations with colour filters: The characteristic features of the Purkinje phenomenon set forth above may be further demonstrated in a striking fashion by the aid of colour filters which transmit limited regions of the spectrum with the wavelength range between 600 and $750\text{ m}\mu$, but cut off the rest of that spectral range. Three such filters have been made use of by the author, prepared by staining gelatine plates respectively with the dye-stuffs (i) disulphine blue, (ii) Coomassie brilliant blue and (iii) methyl violet. The transmission bands of the three filters covered the following wavelength ranges (i) 700 to $730\text{ m}\mu$, (ii) 650 to $700\text{ m}\mu$ and (iii) 630 to $670\text{ m}\mu$.

The luminosity of these strips of transmission in the red region of the spectrum relatively to the parts of the spectrum in the wavelength range between 500 and $600\text{ m}\mu$ passed by the filters can be observed by viewing a continuous spectrum through the filters. It is found to depend to a very great extent on the brightness of the light source employed. It is also very different for the regions of the spectrum in the red transmitted respectively by the three filters.

Concluding remarks: We may sum up the results which have emerged by the statement that the Purkinje phenomenon owes its origin to the spectroscopic

properties of the ferric form of the heme pigment. The observed characters of that phenomenon are a demonstration of the correctness of the identification of the ferric form of heme as the visual pigment which functions in the red sector of the spectrum.

The new physiology of vision—Chapter XV. The chromatic responses of the retina

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It is of fundamental importance for an understanding of the nature of vision to know how the retina in the living state reacts when light is incident on it. Neither anatomy nor biochemistry can possibly furnish us with that knowledge. We may here recall how immensely useful the ophthalmoscope is by its enabling us directly to view the living retina and observe its state or condition. Likewise, it is evident that any technique by which the process of the excitation of the retina by light is brought within the scope of direct observation would be of the highest importance for our understanding of the visual processes. Soon after the author commenced the investigations of which the results are described in the present treatise, a technique was developed by him which had evidently great possibilities of becoming just such a tool of research as that envisaged above. Since then the technique has been improved to such an extent as to make it a precise and reliable method for the study and analysis of our visual sensations. We shall proceed to describe and explain the technique and to indicate in general terms the nature of the results which emerge.

The principle of the method: The essence of the method of observation is the use of a colour filter which freely transmits light over the entire range of the visible spectrum except over a limited and well-defined region which it completely absorbs. It is possible by the use of suitable dye-stuffs in appropriate concentrations to prepare colour filters of gelatine films on glass exhibiting the spectroscopic behaviour described. Holding such a colour filter before his eye, the observer views a brilliantly illuminated screen for a brief interval of time and then suddenly removes the filter while continuing to view the screen with his attention fixed at a particular point on it. He then observes on the screen a picture in colours which is the chromatic response of the retina to the light of the colour previously absorbed by the filter and which impinges on it when the filter is removed. Actually, as will become clearer presently, what the observer sees is a highly enlarged view of his own retina projected on the screen and displaying the response of the retina in its different areas produced by the incidence of the light of

the selected wavelengths. By using a whole series of colour filters whose characteristic absorptions range from one end of the visible spectrum to the other, we are enabled to explore the behaviour of the retina over an extensive region (including especially the foveal area) under excitation by light of different wavelengths which in the aggregate cover the entire visible spectrum.

Why the phenomenon described above manifests itself is not difficult to understand. A colour filter completely absorbing a selected part of the spectrum when placed before the eye of the observer protects the retina from the incidence of light from that part of the spectrum, and if such protection continues for a sufficient period of time, it has the result of sensitising the retina for the reception of light of those wavelengths when the filter is removed. *Per contra*, light of wavelengths not absorbed by the filter being incident on the retina both when the filter is in position and after its removal, the visual sensation which it excites becomes enfeebled by the continued exposure. Accordingly, when the filter is removed, the visual response of the retina to light of the wavelengths for which its sensitivity has been enhanced is far stronger than the continuing response to the other wavelengths and manifests itself vividly to perception. The nature of the picture seen is determined by the part of the spectrum which is absorbed by the colour filters and differs enormously for the different filters employed in the study. The usefulness of the technique for the study of the functioning of the retina over its different areas is thereby vastly enhanced. As in the analogous case of the Haidinger brushes discussed in an earlier chapter, we have to take note of the essentially fugitive nature of the phenomenon. But here, again, this is no obstacle to the study of the effects. For, the image of the retina seen by the observer on removing the colour filter and which fades away is restored and can be examined again and again merely by putting back the filter in front of the eye for a little while and then removing it.

Preparation and use of the colour filters: From what has been stated above, it will be evident that the quality of the filters employed is of great importance. This includes especially the complete transparency over the visible spectrum except in a limited region where there is a complete absorption. It is therefore useful to record here how such filters are prepared. Old and unused photographic plates form excellent material for their fabrication. They are first put in a fixing bath in a dark room and kept long enough to completely remove the sensitive material. They are then washed in running tap-water for half an hour to eliminate all traces of the material of the fixing bath. The plates are then taken out and put in a tray containing distilled water and allowed to remain there for the gelatine to become quite soft. This is necessary to enable the gelatine to absorb the colouring material quickly and evenly. A small quantity of the selected water-soluble dye is put into a beaker containing distilled water and stirred well. The solution obtained is then filtered through a clean cloth to remove any undissolved

particles and the clear solution poured into a developing dish of appropriate size. The plate is then immersed in the solution of the dye-stuff and by varying the time of such immersion (depending on the particular dye-stuff) the depth of colour taken up by the gelatine can be controlled. Several different shades of colour on different plates can thus be obtained. The dyed plate is then taken out and washed in water quickly and kept aside for drying. The filters thus prepared are labelled and kept arranged in closed boxes for use as and when needed.

From amongst the numerous dye-stuffs available, several were selected after a preliminary examination of the transmission of light by their aqueous solutions. In all, some 30 different dyes were chosen and some 150 colour filters were prepared therefrom. Four, or five, or six different depths of colour were fixed on plates for each dye, as the comparative study of the effects observed with such a sequence of filters was found to be useful and instructive. To examine the spectral transmission by the filters, the most convenient procedure is for the observer to view the first-order diffraction spectrum of the glowing filament in a tubular lamp through a replica grating and the filter held together before his eye, and to notice the effect on the spectrum of removing the filter. The comparison with each other of the filters of different depths of colour made with the same dye can be quickly effected in this fashion.

For an observer to study the results of using the colour filters in the manner explained above, a screen of the kind used for projection work containing a great many small glass spheres embedded in plastic is found to be particularly suitable. Placed facing the windows in a well-lighted room, such a screen is quite brilliant and this indeed is necessary for any impressive phenomena to be observed. With a screen 175×120 cm in area, 350 cm is a convenient distance from the screen for the observer to station himself. The area of the screen under observation is then of sufficient width to include an enlarged picture of an extensive region of the retina. That what the observer notices when the filter is removed is a picture of his own retina becomes evident when it is remarked that the foveal disk is the central feature seen in every case. This is located at and around the point on the screen at which the observer's attention is fixed at the instant of withdrawing the filter from before his eye.

We shall proceed to describe one after another the effects observed with the filters prepared with various individual dyes and their relation to the spectral characteristics of the filter. The integrated picture of the retina which emerges from these studies will form the subject of a later chapter.

Filters of crystal violet: Colour filters prepared with this dye exhibit quite spectacular effects. Extremely conspicuous is the brilliant disk of green colour appearing at the centre of the field around the point of fixation of vision at the instant of removal of the filter. Its position as well as the actual size of the disk show it to be a highly enlarged image of the fovea of the observer's own retina. At the centre of the disk a bright spot can be seen which is evidently the foveola, in

other words, the bottom of the foveal depression in the retina. The foveal disk also exhibits a rim which is distinctly brighter than the region inside. The foveal disk also exhibits a rim which is distinctly brighter than the region inside. There are also indications of a radial structure visible within the area of the disk. Outside the foveal disk and concentric with it, the observer notices an extensive area of circular shape of which the diameter is some five times greater than that of the foveal disk, but which is much less luminous than the latter. This area exhibits a greenish-yellow colour, much less saturated in hue than the green of the foveal disk. The outer margin of this area appears fairly well defined. Beyond this circular area and surrounding it is a region exhibiting an orange-yellow colour.

A sketch of the effects described above is reproduced as figure 1. The differences in colour and luminosity between the foveal disk and the surrounding areas cannot, of course, be properly exhibited by shading in a black and white sketch. Even the details of the structures seen visually within the foveal area cannot thus be exhibited. Nevertheless, the figure may help to convey some idea of the effects observed, supplementing a purely verbal description.

All the five filters prepared with crystal violet exhibit a blue colour by transmitted light, but the depths of their colours are very different. The effects described above are shown only by those filters which had been dyed to a sufficient depth of colour to make the absorption by crystal violet really effective. Only in three out of the five filters which were prepared was this actually the case. Spectroscopic examination shows that the absorption by the dye manifests itself as two distinct bands, one in the green and the other in the orange, the former ranging from 540 to 570 $m\mu$, and the latter from 590 to 620 $m\mu$. In the most heavily-dyed filter, these bands have spread out and their overlap results in a complete cut-off of the region of wavelengths between 530 and 640 $m\mu$, while the rest of the spectrum is transmitted without any noticeable absorption. In the two less heavily-dyed filters the two bands can be seen to be distinct from each other, but nevertheless the absorption of the yellow of the spectrum in the wavelength range between 570 and 590 $m\mu$ is quite strong. The absorption of the yellow is however quite weak in the fourth filter of the series and scarcely noticeable in the fifth.

A comparative study of the effects observed with all the five filters is highly instructive when considered in relation to their respective spectroscopic behaviours. Even with the most lightly-dyed filter, it is possible for the observer to notice on the illuminated screen a picture of his own retina. But for this to be possible, it is necessary to hold the filter before his eye for a longer period before removing it than in the case of the more highly-coloured filters. In the picture then seen, the orange-yellow field in the outer region is the most conspicuous feature, while the circular area and the foveal disk which it surrounds too are scarcely noticeable. But these features appear more distinctly with the next filter in the series, while with the three other filters, they become progressively more and more conspicuous.

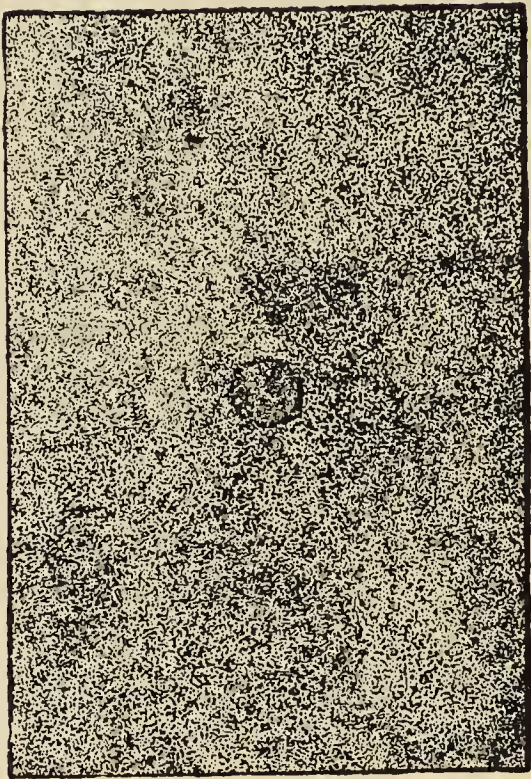


Figure 2. Foveal disk and surrounding area.

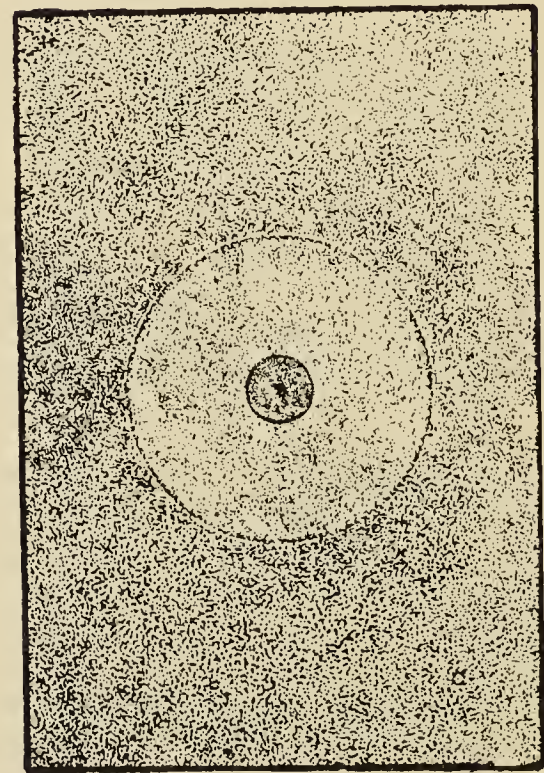


Figure 1. Foveal disk and surrounding area.

From what has been stated above, it is apparent that the absorption of light by the filters in the yellow region of the spectrum, viz., between 570 and 590 $m\mu$, plays a highly important role in giving rise to the observed effects. Indeed, only when such absorption is present do we observe the very striking manifestation of a brilliantly luminous disk in the foveal area. That the disk appears of a green colour and not just yellow is an indication that the absorption by the filter of the spectral region between 540 and 570 $m\mu$ also then takes part in exciting the foveal region of the retina. The co-operation of the entire region of the spectrum between 540 and 590 $m\mu$ is clearly needed for observing the brilliant foveal disk as well as the much larger circular area which appears surrounding it. On the other hand, the absorption of the part of the spectrum between 590 and 640 $m\mu$ gives rise to the orange-yellow hue observed in the outer parts in the field. Its effect on the region of the fovea and the area immediately surrounding the fovea is submerged in the much larger contributions arising from the spectral region between 540 and 590 $m\mu$.

Filters of methyl violet: This well-known dye-stuff is closely related to crystal violet in its chemical constitution and its spectroscopic behaviour also resembles that of crystal violet. It is, however, not very easy with it to prepare a set of colour filters of the same high quality as with crystal violet. This may be due to impurities present in the commercially available material. Nevertheless, the filters actually prepared with it which have the necessary depth of colour exhibit effects similar to those observed with crystal violet and approaching them in their spectacular character. The most striking results are those observed with filters which show a complete extinction in the spectral range between 540 and 630 $m\mu$ and perfect transmission in other parts of the spectrum. Thus, they support the same conclusions as those based on the observations made with crystal violet.

Cyanin filters: A set of six filters were prepared with this well-known dye-stuff, their colours by transmitted light ranging from a deep blue to a light blue. The absorption spectra of the filters showed a regular progression, the deepest filter exhibiting a practically complete extinction of the yellow, orange and red regions in the spectrum, while the lightest filter showed a well-defined absorption band in the wavelength range from 630 to 670 $m\mu$. The visual effects produced and observed with these filters also alter in a progressive fashion. With the filter which exhibits a cut-off extending from the yellow towards greater wavelengths, the observer notices a disk of yellow light with a bright spot at the centre and a bright rim around its margin appearing in the foveal region. Surrounding this and exhibiting a yellow colour, a circular area also manifests itself which has a diameter some three times greater than that of the foveal disk. Outside this again, there is a field of light extending to the outer limits of the screen and exhibiting an orange hue.

Observations with the other five filters show that the yellow foveal disk and the surrounding yellow region become less and less prominent in the series relatively to the outer parts of the field. With the two lightest filters, they can be observed only with some difficulty. On the other hand, the outermost areas continue to be visible and to exhibit colour. This colour shows a perceptible change from an orange to a reddish hue in the sequence.

From these observations, we are led to infer that the foveal region and the brighter area immediately surrounding it are made conspicuous by reason of light in the spectral range between 570 and 590 $m\mu$ being incident on the retina. On the other hand, the orange and the red sectors of the spectrum are responsible for the luminosity appearing in the outer parts of the field.

Filters of disulphine blue V.S: Five filters were prepared with this commercially available dye-stuff. The first two gave a complete extinction of the yellow region of the spectrum and of all greater wavelengths. The absorption in the yellow was very weak with the third filter and non-existent with the fourth and the fifth. These three filters exhibited a powerful absorption in the orange and red sectors of the spectrum, a dark band in the wavelength range between 630 and 670 $m\mu$ being a conspicuous feature.

With the two filters which gave a perfect extinction of the yellow, observations showed the foveal region as a bright yellow disk with a luminous spot at the centre and a bright rim around the margin. Surrounding this was a circular region which was less luminous and had a diameter some three times greater than that of the foveal disk. The rest of the field exhibited an orange-red glow. Only the latter phenomenon was exhibited by the three weaker filters, barely a trace of the foveal disk and of the surrounding region being distinguishable from the rest of the field. Thus, the observations point to conclusions similar to those indicated by the observations with the cyanin filters.

Colour filters of magenta: A set of three filters were prepared with this well-known dye-stuff. All three showed a strong absorption in the wavelength range from 550 to 580 $m\mu$, accompanied by a weaker and more diffuse absorption in the wavelength range between 500 and 550 $m\mu$, while the rest of the spectrum showed no observable diminution of intensity in its passage through the filter. In effect, the most heavily-dyed filter cut off the whole of the green in the spectrum, while the other two filters were less effective in this respect.

All the three filters behave similarly when held by the observer before his eye and then quickly removed while he continues to view the illuminated screen with his attention fixed at a particular point in it. The only difference noticeable as between them is that the less strongly-dyed filters have to be held before the eye for a longer interval of time before being removed. Following the removal of the filter, the entire area of the screen exhibits a greenish-yellow glow which vanishes

after a few seconds. But it may be instantly restored by putting back the filter and then removing it again. In effect, the observer sees on the screen a projection of his own retina as illuminated by light in the wavelength range between 550 and 580 $m\mu$. This is made evident by the appearance at the centre of the field of a disk which does not exhibit the greenish-yellow glow seen over the rest of the screen and which is differentiated from the surrounding area by its relative feebleness and its pale blue colour.

From the foregoing, it emerges that the effects observed with the magenta filters are strikingly different from those exhibited by the other filters and described in the preceeding paragraphs. These differences are clearly attributable to the regions of the spectrum exciting the response of the retina being different. It may be remarked that in the present case, we are concerned exclusively with the response of the retina to light appearing in the green sector of the spectrum.

Colour filters of rhodamine B: Four filters were prepared with this well-known dye by varying the time of immersion of the gelatine film in the bath of its solution. The depth of the colour exhibited by them in transmitted light showed the progressive change to be expected in the circumstances. Even the most lightly-dyed filter shows a complete extinction of light in the wavelength range between 540 and 580 $m\mu$. In the more heavily-dyed filters, this absorption band widens asymmetrically towards shorter wavelengths, resulting in a complete extinction of the green region in the spectrum. A spread of the absorption towards longer wavelengths in the more heavily-dyed filters is also noticeable, but the yellow and orange of the spectrum are not totally extinguished. Thus the effect of the rhodamine filters is principally to block out the green of the spectrum. The phenomena observed with them are essentially similar to those noticed with the magenta filters. It is therefore unnecessary to describe them here again in detail.

Yellow colour filters: Various dyes when incorporated into gelatine films result in filters exhibiting a yellow colour by transmitted light. Auramine-yellow may be mentioned as a good example of such a dye-stuff. Spectroscopic examination shows that when the absorption is confined to the extreme violet end of the spectrum, the colour of the transmitted light is a pale yellow. As it progresses further and covers more of the spectrum, the colour deepens. Finally it becomes a rich golden-yellow when all wavelengths less than 500 $m\mu$ have been cut off. A further advance into the green of the spectrum beyond 500 $m\mu$ results in the transmitted light exhibiting orange-yellow hues.

Observations made with all such filters exhibit certain common features. Following the removal of the filter from before the observer's eye, a glow of colour appears over the illuminated screen, its brilliance depending notably on the depth of colour of the filter as also on the period of time for which the filter is held before the eye prior to its removal. The colour of the glow ranges from violet to blue or a

bluish-white, depending on the extent of the spectral cut-off by the filter employed. At the centre of the field around the point of fixation of his vision, the observer notices a circular area—evidently the projected image of the fovea of his own retina—where the glow referred to above is absent and a pale yellow hue is perceived instead (figure 2 attempts to represent this effect by a black and white sketch.) A dark spot is sometimes also seen at the centre of the foveal disk, with some indications of structure within the area.

The new physiology of vision—Chapter XVI. Further studies of the retinal responses

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In the present chapter will be set out the results of the study of the functioning of the retina by the method which makes use of special colour filters as has been fully explained in the preceding chapter. Observations with thirty filters made with seven different dye-stuffs have already been described in that chapter. The results which emerged are sufficient by themselves to lead to definite conclusions. However, many more filters had been fabricated with several other dye-stuffs and it was considered desirable to complete the study making use of such of them as are suitable for the observations. The results obtained and set forth here confirm and in certain respects usefully supplement the earlier findings. The significance of these findings in relation to the structure and functioning of the retina will be discussed in the next chapter.

Filters of cotton blue: This dye-stuff incorporates itself smoothly into gelatine films, making admirably clear filters exhibiting a blue colour of which the depth is determined by the quantity of the dye taken up. Spectroscopic examination shows that the absorption by the dye is strongest in the yellow region of the spectrum, viz., at $580\text{ m}\mu$. The filters are completely transparent to the shorter wavelengths in the spectrum up to about $550\text{ m}\mu$. Beyond the yellow again there is a sensible absorption which results in the orange and red of the spectrum being much weakened.

When such a filter is held before the eye of the observer who views a brightly-illuminated white screen for a little while and the filter is then removed with the vision fixed at a particular point on the screen, a picture of the observer's retina flashes into view. The most conspicuous feature in the picture is a bright yellow disk which is an enlarged image of the fovea with a bright yellow spot at its centre and a distinctly brighter rim around its margin. Encircling the foveal disk appears an area of circular shape with a fairly well-defined outer margin. This has a diameter some four times greater than that of the foveal disk. The colour of this region is yellow with a slight greenish tinge. The rest of the screen displays a glow of which the yellow hue is readily distinguishable from the colours noticed in the regions which it surrounds.

Filters of coomassie brilliant blue: This dye-stuff when incorporated into gelatine films makes very satisfactory filters. Their colour as seen by transmitted light alters progressively from a light to a deep blue as the quantity of the dye taken up is increased. The filters prepared were transparent to the whole visible spectrum except in the region between 550 and 630 $m\mu$. This region which includes the greenish-yellow, yellow and orange sectors is totally absorbed by the more heavily-dyed filters. In the observations made in the usual manner with such filters, the most conspicuous feature is the foveal disk with a bright spot at its centre and a bright rim around its margin. It exhibits a greenish-yellow colour. The foveal disk appears encircled by a circular region which is less luminous but much larger in area. This again appears surrounded by a field exhibiting an orange-yellow hue. From the observed features, it is evident that the foveal disk and the luminous area immediately surrounding it owe their origin to the absorption by the filter appearing between 550 and 590 $m\mu$, while the orange-yellow glow appearing in the outer parts of the field arises from the spectral region between 590 and 630 $m\mu$.

Filters of bromophenol blue: Three filters dyed to different depths were obtained with this material, the colour exhibited by them in transmitted light showing the progression from a lighter to a deeper blue to be expected in the circumstances. Spectroscopic examination of the transmitted light showed with all the three filters, a band of complete extinction in the wavelength range between 590 and 630 $m\mu$ covering the orange sector of the spectrum. In addition, an absorption was also exhibited in the wavelength range between 560 and 590 $m\mu$ covering the greenish-yellow and yellow parts of the spectrum. This absorption was relatively weak in the first of the three filters, much stronger in the second filter and practically complete in the third filter.

The effects exhibited to the observer's vision with the three filters showed very clearly a progressive change. The foveal disk and the luminous area immediately surrounding it were only dimly seen with the first filter, were much stronger with the second and very conspicuous with the third. The colour exhibited by the foveal disk was a pale greenish-yellow and that of the area immediately surrounding it which was less luminous appeared to be the same. On the other hand, the outer parts of the field exhibited an orange-yellow hue.

Filters of coomassie violet: Excellent colour filters are produced by incorporating this dye-stuff into gelatine films. The colour of the light transmitted by the filters may be described as rose-red. Spectroscopic examination shows the filters to be completely transparent to all parts of the spectrum except the green in which there is an absorption band covering the wavelength range between 520 and 570 $m\mu$, the strongest absorption being at 545 $m\mu$. It is necessary to hold the filter in front of the eye for at least a couple of minutes on the first occasion before removing it in order to perceive the effect which results from its removal, viz., a

greenish-yellow glow covering the entire screen except the foveal area at the centre of the field. This latter area appears quite dim, the glow seen elsewhere being totally absent in it. The phenomenon can be seen again and again, merely by putting back the filter before the eye and then removing it.

Filters of phloxine: Two filters had been prepared with this dye, one of them being more strongly dyed than the other. Spectroscopic examination shows the absorption by the phloxine filters to be exclusively in the green of the spectrum, there being complete transparency in other parts. The more deeply-dyed filter shows a complete cut-off of the spectral region from 535 to 570 $m\mu$ coupled with a strong absorption from 500 to 535 $m\mu$. The less heavily-dyed filter shows a strong absorption in the wavelength range from 540 to 565 $m\mu$. Both filters give effects generally similar to those observed with the coomassie-violet filters and briefly described above.

Colour filters of fast green: A set of five filters prepared with this dye-stuff exhibit the characters best suited for such studies, viz., perfect transparency over an extended region of the spectrum and a complete extinction in other regions. The filters show a regular progression of the colour as seen by transmitted light, viz., from a bright blue for the most heavily-dyed to a greenish-blue for the most lightly dyed. Spectroscopic examination shows a complete cut-off of all wavelengths greater than 560 $m\mu$ by the first filter. With the second filter, the cut-off has shifted to 580 $m\mu$ and with the third to 590 $m\mu$. The fourth filter shows nearly perfect transparency up to 590 $m\mu$ while the orange and red regions have begun to appear in the transmitted light, a strong absorption showing itself in the red between 620 and 670 $m\mu$. With the fifth and last filter, only this absorption can be seen, the rest of the spectrum being transmitted freely.

The yellow foveal disk with a bright spot at its centre and a bright rim is the most conspicuous effect observed with the first filter. It is less conspicuous with the second filter and only with difficulty observable with the third and fourth filters. It is not visible with the fifth filter. A similar sequence of changes is observed in respect of the circular area which surrounds the foveal disk. On the other hand, the glow seen over the rest of the screen following the removal of the filter is a conspicuous feature in all cases. There is a clearly noticeable change in the colour of this glow, an orange yellow with the first filter, an orange with the second and third filters, an orange red with the fourth and just red with the fifth and last filter.

Colour filters of brilliant green: The four filters exhibiting a green colour by transmitted light prepared with this dye-stuff showed effects of a distinctive character, arising from the circumstance that they exhibit absorption at both ends of the spectrum. The absorption in the region of the shorter wavelengths extends up to 450 $m\mu$ and is conspicuous with the heavily-dyed filters, but is also

noticeable with those more lightly dyed. In the region of long wavelengths, the yellow, orange and red sectors are completely absorbed by the heavily-dyed filter. The filters which are more lightly dyed exhibit little or no sensible absorption in the yellow. Their absorption is principally in the orange and the red where a dark band manifests itself in the wavelength range from 620 to 670 $m\mu$.

The yellow foveal disk with its usual accompaniments is quite conspicuous in observations made with the most heavily-dyed filter of the set. It is much less so with the second filter and scarcely observable with the third and fourth filters. Very striking also is the rose-red glow which appears covering the whole field following the removal of the filter in all cases. This phenomenon is clearly the result of the superposition of the glows produced by the parts of the spectrum at both its ends which are absorbed by the filter and which impinge on the retina when it is removed.

Colour filters of tropaeolin: Three filters were prepared with this dye-stuff which by transmitted light exhibited respectively a golden yellow colour, a deep yellow and an orange-yellow hue respectively. The first of the three filters showed a cut-off of the shorter wavelengths in the spectrum upto 450 $m\mu$ and a noticeable absorption up to 500 $m\mu$. With the second filter, the cut-off has shifted to 490 $m\mu$ with a perceptible absorption up to 510 $m\mu$. The third filter exhibits a cut-off at 500 $m\mu$ and an appreciable absorption up to 520 $m\mu$.

Observations with these three filters showed the effects already noticed with the auramin-yellow filters and described in the preceding chapter. Following the removal of the filter from before the eye of the observer, he notices a coloured glow over the screen, this however being definitely absent at the centre of the field in a circular area corresponding to the projection of the fovea of his retina on the screen. The colour of the glow is violet for the first, blue for the second filter and bluish-white for the third, the brilliancy of the glow increasing in that order. A dark spot at the centre of the foveal disk is very clearly seen. There are also indications of a radial structure in the foveal area.

Colour filters of acridene orange: Four filters were prepared with this dye-stuff. By transmitted light they exhibit a light orange hue in the case of the first filter, and progressively deeper orange hues for the others in the series. Spectroscopic examination showed that the first filter extinguishes all the shorter wavelengths in the visible spectrum up to 525 $m\mu$. The wavelength of cut-off shifts to 535 $m\mu$ for the second filter, to 545 $m\mu$ for the third filter and to 550 $m\mu$ for the fourth.

The effects observed with the first of the acridene orange filters are very similar to those exhibited by the third of the series of tropaeolin filters. In particular, the darker region at the centre of the field corresponding to the fovea was quite clearly seen. With the more heavily dyed filters of the series, this central region is less well-defined and less clearly observable. The appearance of the screen following the removal of the filter does not indeed differ very much from its appearance in the absence of the filter. A short-lived bright glow with a hint of blue in it is all that is actually observed.

The new physiology of vision—Chapter XVII. Location of visual pigments in the retina

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We proceed to consider the significance of the results of our studies on the chromatic responses of the retina and to view them in the light of the conclusions regarding the identity and spectroscopic behaviour of the visual pigments arrived at in earlier chapters. For this purpose, it is necessary to summarise the results of those studies. As has already been explained, what the observer notices when he views a brightly illuminated screen through a colour filter and then suddenly removes the filter depends very much on the spectral region in which the absorption by the filter is manifested and hence differs from filter to filter.

On the basis of the observed phenomena the part of the visible spectrum in which the absorption by the filter is effective may be placed in any one of the following four divisions, viz., I: from 4,000 to 5,000 A.U.; II: from 5,000 to 5,600 A.U.; III: 5,600 to 6,000 A.U. and IV: from 6,000 to 7,000 A.U. These regions will, in what follows, be referred to as the blue, green, yellow and red sectors of the spectrum, these being the colours which are dominant respectively in these four regions. The picture of the retina as perceived by the observer following the removal of the filter may likewise be divided into three regions. A: the fovea; B: a circular area surrounding the fovea and having a well-defined margin and a diameter about four times that of the fovea; C: the surrounding field. The luminosity and colour exhibited by these regions are related to the spectral region of absorption by the filter in the clearly definable fashion. We may indeed say that the part or parts of the spectrum in which the absorption by the colour filter appears determines the picture seen of the retina in all its details.

By far the most spectacular effects are those observed with the colour filters of which the absorption completely covers the yellow sector of the spectrum. Indeed, the phenomena observed with such filters are altogether different from those observed with the filters which exhibit absorption exclusively in the blue, green or red sectors. The striking feature exhibited by them is the manifestation of the fovea as a luminous disk conspicuous by reason of its brightness which much exceeds that of the surrounding areas. Surrounding the foveal disk and of a lesser brightness, but nevertheless clearly differentiated from the outer parts of the field is a circular area having a diameter about four times greater than that of the fovea.

These features are not observed when the filters employed have an absorption lying exclusively in the blue, green or red sectors.

Thus, the observations with the colour filters demonstrate that the yellow sector of the spectrum stands in a class by itself and that it plays a highly significant role in the phenomena of vision. The same conclusion has already been arrived at and stated in earlier chapters on the basis of other considerations. But the new result which now emerges is that the visual pigment which enables us to perceive light appearing in the yellow sector of the spectrum is concentrated in the foveal region of the retina and in the areas immediately surrounding it. Only on that basis is it possible to understand the facts of observation.

The distributions in the retina of the visual pigments which enable us to perceive the blue, green and red sectors of the spectrum are clearly of a different nature. This is made evident by the picture of the retina which is seen when the filter made use of has its absorption in one or another of these three sectors. The glow exhibited by the area of the retina under observation (blue, green, red in colour as the case may be) in the areas surrounding the fovea is of uniform brightness. The fovea itself presents a different appearance in the three cases. With the filters which have a cut-off in the blue, the fovea does not exhibit the blue glow but is seen as a disk with a sharply defined edge and of a pale yellow colour. Likewise, with the filters having a cut-off in the green sector of the spectrum, the fovea does not exhibit the glow seen outside of it, but is seen dimly with a bluish tinge. In the case of the filters having a cut-off in the red, the glow seen elsewhere covers the fovea as well.

Thus, a systematic survey of the retina with the aid of colour filters exhibiting absorption in a relatively narrow range of the spectrum but which between them cover the entire visible spectrum from end to end enables us to establish the result that there are four visual pigments which function in the perception of light in ordinary or daylight vision. It also enables us to indicate the regions of the spectrum on which they respectively function and the manner in which they are distributed over the retina.

In earlier chapters, the visual pigments functioning in the yellow and green sectors of the spectrum were identified respectively as the fully oxygenated form and as the reduced form of heme. The former identification was based on some very significant facts of observation, viz., that the yellow of the spectrum appears precisely at the same position as the sharply defined peak of light-absorption at $579\text{ m}\mu$ exhibited by oxygenated heme, that a remarkably high power of colour discrimination is manifested in the vicinity of that wavelength and that the spectrum also exhibits a high luminous efficiency in that region. The observations made with the colour filters fit in perfectly with this situation. It is found, as is to be expected in these circumstances, that the retinal pictures alter in a remarkable fashion as the region of absorption by the filter moves from the red into the yellow sector of the spectrum. The foveal disk appears quite suddenly and exhibits at first a yellow hue. It then gains in luminosity and takes on a greenish yellow colour

and finally appears a brilliant green when the absorption by the filter covers the wavelength region between 600 and 560 $m\mu$ and extends further into the green. But filters exhibiting absorption in the green sector alone and not extending into the yellow sector do not produce any such effects.

These experiences are readily understood when we take note of the form of the light-absorption curves of the oxygenated and of the reduced forms of heme in the wavelength range between 600 and 500 $m\mu$. Both forms of heme exhibit a powerful absorption in this range. But the oxygenated form has a sharply defined and intense absorption at 579 $m\mu$, falling off steeply towards greater wavelengths and much less steeply towards shorter wavelengths. It also has a second weak and diffuse maximum of absorption around 542 $m\mu$. The reduced form of heme has only a single wide-band maximum of absorption around 555 $m\mu$ and since this form of the heme pigment is not present in quantity in the region of the fovea, filters of which the absorption appears only in the region between 500 and 560 $m\mu$ do not exhibit any such effects as those described above.

We may here appropriately mention the remarkable changes in the relative intensity of the yellow and green sectors of the spectrum as visually observed which accompany a progressive fall in the absolute intensity of both sectors. These effects may be conveniently observed in the following fashion. The light emerging from a bulb containing luminous mercury vapour is examined through a pocket spectroscope with the slit opened rather wide. The green and yellow lines of the mercury arc spectrum then appear as patches of light side by side exhibiting these colours. A progressive reduction of their absolute luminosities may be readily obtained by interposing a sheet of opal glass between the lamp and the spectroscope and by the observer moving away from the lamp together with the opal glass sheet and the spectroscope. When he is close to the lamp, the green and yellow patches appear of comparable brightness. But when he is at the other end of the room, both the green and yellow patches exhibit their respective colours, but the yellow appears much less bright than the green. When a further reduction of intensity is produced by the introduction of additional diffusing screens, e.g., sheets of white paper, the yellow becomes progressively feebler and in the limit extremely weak relatively to the green, while the latter continues to be readily observable.

The phenomenon described above is obviously complimentary to the enormously enhanced brightness of the yellow region in the spectrum observed at high levels of luminosity and described in detail in an earlier chapter. In other words, the observed fall in luminosity of the yellow relatively to the green at low levels of brightness is a part of the same sequence of changes in the visual luminosity of the yellow sector as that produced by increases in its absolute level of brightness. That this is actually the case may be demonstrated using the same techniques as those employed earlier for observations of the yellow sensation at high levels of luminosity. The spectrum of a straight tungsten filament heated by an electric current is viewed by the observer from an appropriate distance holding

a replica grating before his eye. As the heating current is progressively diminished, it will be noted that the brightness of the yellow sector in the spectrum relatively to the green and the red sectors on its two sides falls off, until it becomes barely recognisable.

The presence of the oxidised form of the heme pigment in notable quantities in the region of the fovea and in a circular area surrounding that region finds a ready explanation if it be assumed that the pigment enters the retina as an exudate from the highly vascular choroid coat immediately behind it. After entering the foveal pit which is the thinnest part of the retina, it would spread symmetrically outwards from it into the surrounding region. If, further, it be assumed that the quantity of the pigment thus made available for vision varies with the demand for it, in other words, with the level of luminosity at which the retina is functioning, the preponderance of the yellow sensation of high levels of luminosity, and its relative weakness or even total absence at low levels of brightness would find a ready explanation. Since the luminous efficiency of the spectrum in the wavelength range from 600 to 500 $m\mu$ is determined jointly by the oxidised and reduced forms of heme, the relative proportion in which these are present would influence the spectral distribution of luminosity in this range of wavelengths. If the oxidised form is present in prepondering measure, the yellow sector would be much more luminous than the green. If it is absent, or deficient, the green sector would be far more luminous than the yellow.

The presence of the heme pigment in its fully oxidised form in the retina may be expected to involve as a natural consequence its being accompanied by the same pigment in its ordinary or reduced form. The latter pigment exhibits a wide-band absorption maximum located at 555 $m\mu$ which is the same wavelength as that at which the luminous efficiency in the spectrum at normal levels of illumination as reported by various observers is a maximum. Thus, the identification of the reduced form of heme as one of the major visual pigments is, apart from all other considerations, fully justified by the actual facts of vision.

The presence in or behind the retina of a biochemical mechanism by which the oxygenated heme pigment in the ferrous state is transformed by auto-oxidation to the ferric form of the pigment would provide the visual pigment needed for the red sector of the spectrum. The identification of the ferric form of heme as that functioning in the spectral range between 600 and 700 $m\mu$ is confirmed by the fact that it exhibits a peak of absorption at 630 $m\mu$ beyond which the absorption falls off rapidly. This is just what is needed to explain the rapid change of colour from orange to red which appears at 630 $m\mu$, beyond which the change of colour becomes extremely slow. Further, the spectroscopic behaviour of the ferric form of heme is precisely that needed to account for the observed features of the Purkinje phenomenon which have been fully described and discussed in an earlier chapter.

The new physiology of vision—Chapter XVIII. The visual synthesis of colour

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In the preceding chapters, we have been principally concerned with monochromatic light and the sensations excited by it. But in most cases of practical interest, the light which reaches the eye of an observer and enables him to perceive the objects around him is not monochromatic but is composite in character. As a consequence, the visual sensations result from the superposition of light appearing in various parts of the spectrum. The spectral nature of the light emitted by the original source and the optical properties of the objects on which it falls and from which it reaches the eyes of the observer determine its character. Hence, what the eye perceives is the integrated effect of light distributed over the visible spectrum, and a process which may be called the visual synthesis of colour is involved in the perception. This is evidently a subject which is highly important both from a practical point of view and from the standpoint of physiological theory. It will receive detailed consideration in this and the following chapters.

From the nature of the subject, it is evident that our understanding of it has to be based on the actual facts of experience in various cases, these being sufficiently numerous and representative to enable valid inferences to be drawn therefrom. What we wish to ascertain is the general nature of the relationship between the perceived colour and the spectral composition of the light which reaches the eyes of the observer. The latter can, of course, exhibit a wide range of variations and the question arises how it should be ascertained and specified. The further question arises how the perceived colour is to be characterised and described. The problems here stated indicate the complexity of the subject. The choice of the material utilized for such studies is evidently a matter of importance. It should be such as to minimize the difficulties of the investigation.

In the present chapter, we shall set out the results emerging from a study of the visual synthesis of colour made with material which is in a particularly suitable and convenient form, viz., colour filters which absorb a limited part of the spectrum more or less completely and freely transmit the rest of it. It will be recalled that a great many filters of gelatine-on-glass dyed with suitable colouring matters were specially fabricated and made use of for the studies described in earlier chapters. Such filters have been utilised also in the present studies. Colour

filters can also be prepared by dissolving a small quantity of a dye-stuff or other material in distilled water contained in a rectangular glass cell of suitable dimensions ($10 \times 10 \times 2 \text{ cm}^3$). By varying the quantity of absorbing material put in, its effective thickness can be varied and the resulting changes in the colour and the spectral nature of the transmitted light can be conveniently followed.

Colour filters of cyanin: We shall now describe in detail, the observations made with a set of seven filters of gelatine-on-glass coloured by the well-known dye-stuff cyanin to different extents and thus exhibiting the effect in a regular sequence of an increasing measure of absorption, both on the colour of the transmitted light and on its spectral character.

To study the character of the spectrum of the light transmitted by a filter, a convenient plan is for the observer to hold a replica diffraction grating in front of his eye and to view the first-order diffraction spectrum of a linear tungsten filament in a tubular lamp glowing at a white heat. Introducing the filter in front of the diffraction grating, the change in the spectrum produced thereby can be quickly noted. It then becomes evident that absorption by the cyanin filters is limited to the yellow, orange and red sectors of the spectrum, while the blue and the green sectors are transmitted without any noticeable loss in intensity. The absorption in the red sector takes the form of a well-defined absorption band, which in the case of the weakest filter may be located in the wavelength range $620\text{--}650 \text{ m}\mu$. In the other filters of the series, this band becomes more pronounced and also becomes wider, the spreading being asymmetrical and chiefly towards the lesser wavelengths. Even through the most heavily dyed filter, the red end of the spectrum in the region of $700 \text{ m}\mu$ continues to be freely transmitted.

Simultaneously with the increase of the absorption in the red, the absorption in the yellow and orange becomes intensified, until finally with the most heavily dyed filter, we have a continuous absorption commencing at $570 \text{ m}\mu$ covering the yellow and orange sectors and joining up with the absorption band in the red mentioned above. It is noteworthy that even with the most heavily dyed filter, there is no observable absorption in the region of wavelengths less than $570 \text{ m}\mu$. In particular, the green of the spectrum comes through with full intensity.

The colour of the light transmitted by the filters as seen by holding them against a clouded sky may be described as blue in all cases. There is, however, an observable progression which can be described as an increase in the depth of the colour or alternatively as an increase in the degree of its fullness or saturation. These changes, it should be remarked, go hand in hand with the increase in the absorption in the yellow sector of the spectrum between 570 and $590 \text{ m}\mu$. Indeed, it would be correct to say that the blue colour of the light transmitted by the filters exhibits fullness or saturation to an extent determined by the completeness of the absorption of the yellow.

With the disappearance of the yellow sector of the spectrum, and the extinction of the greater part of the red sector, we are still left with the blue and green sectors

which are present in full strength. It is remarkable that there is scarcely any indication in the perceived colour of the green sector which is seen with great intensity on the spectrum of the light which passes through the filter.

The cuprammonium filter: Dissolving copper sulphate in distilled water and adding ammonia in excess, we obtain a solution exhibiting a characteristic blue colour. When the concentration of the solution is high, the transmission by it is confined to the region of the shortest wavelengths and indeed, the cuprammonium filter is usually employed for isolating this part of the spectrum. When, however, the solution contained in a cell 2 cm thick is progressively diluted by addition of distilled water, striking changes may be observed in the spectrum of the light transmitted by it. The transmission, which at first is confined to the violet end of the spectrum, extends towards longer wavelengths. It ceases to be confined to the blue region of the spectrum and the green sector is also transmitted. This progressively gains in strength until as seen through the spectroscope, the green actually appears more luminous than the blue sector. With further dilution, the transmission extends into the orange and the red of the spectrum, but the yellow region remains faint, the orange and the red much exceeding it in brightness. Throughout this series of changes, the colour of the transmitted light is perceived as blue, the depth or saturation of the colour diminishing notably in the case of the very dilute solutions. The observations thus make it evident that the blue colour of the transmitted light and the extinction of the yellow in its spectrum are connected phenomena.

Solutions of potassium dichromate: Commencing with a concentrated aqueous solution of potassium dichromate and progressively diluting it with distilled water, we can readily follow the changes in the perceived colour of the light transmitted through a definite thickness of the solution in relation to its spectral character. The concentrated solution is of a deep orange hue and the spectrum exhibits a cut-off of all wavelengths less than $565\text{ m}\mu$. A considerable measure of dilution is needed before there is any marked change of colour or a noticeable shift in the position of the cut-off. Step by step, however, these changes may be effected and as the cut-off moves from 565 to $520\text{ m}\mu$ the colour alters progressively from a deep orange to a rich golden-yellow. On further dilution, the cut-off becomes less sharply defined and moves from the green into the blue sector of the spectrum. The colour then alters to a bright yellow and then to paler and paler shades of yellow. So long, however, as even a tinge of yellow is observable in the colour of the transmitted light, the absorption at the short-wave end of the spectrum continues to be noticeable.

Solutions of cobalt sulphate: An absorption of light in the green of the spectrum covering the wavelength range between 500 and $550\text{ m}\mu$ coupled with a free transmission of the longer wavelengths is manifested by moderately strong

aqueous solutions of cobalt sulphate. Stronger solutions exhibit an absorption extending to about $575\text{ m}\mu$ and appear of a deep orange colour by transmitted light, while weak solutions exhibit a colour varying from a rose-red to an orange-red depending on the extent of dilution. There is an observable transmission through the solutions of the shorter wavelengths in the spectrum. But such transmission does not appear to have any marked effect on the colour of the transmitted light.

Solutions of nickel chloride: Aqueous solutions of this crystalline salt exhibit notable variations in the brightness and colour of the transmitted light as the concentration of the salt is varied. These changes are most conveniently exhibited by filling a set of bottles of the same size with solutions of different concentrations and placing them side by side against the same white background so that their differences in appearance are evident at a glance. The relationship of the colour to the spectral character of the light transmitted through the solution can also be followed with the aid of a pocket spectroscope.

The green colour of solutions of nickel chloride is a consequence of an absorption of light which manifests itself at both ends of the spectrum, the intermediate parts being freely transmitted. When solutions of different concentrations are set side by side and compared with other, it is found that a very striking change occurs when the cut-off of the longer waves shifts its position from about 570 to $590\text{ m}\mu$. In the former case, the yellow of the spectrum is completely cut off, while in the latter case it is freely transmitted. As a result, the transmitted light notably gains in intensity and its colour changes from a clear green to a green tinged with yellow. Greater dilutions in which the cut-off shifts further into the red result in less noteworthy changes. The highly important role played by the yellow sector of the spectrum in determining the colour of the transmitted light is thus made apparent.

Solutions of chromium chloride: Strong solutions of the chloride of chromium exhibit a deep green colour which owes its origin to a transmission in the 500 – $550\text{ m}\mu$ region of the spectrum. Holding up a cell containing such a solution against a strong light and examining the light coming through it with a pocket spectroscope, the transmission band in the green sector is found to be accompanied by another located near the red end of the spectrum. It is the intermediate region containing the yellow of the spectrum which is most strongly absorbed. Dilution by successive additions of distilled water results in a large increase in the brightness of light transmitted by the cell, but there is no very pronounced change in its colour. Spectroscopic examination in these circumstances reveals that the band of transmission in the green has broadened in either direction and that the red sector has also made its appearance in the transmitted light. When the dilution has been carried far enough, the red region of the spectrum is quite conspicuous and it is only a little less bright than it is normally.

It seems surprising that in the circumstances stated above, the colour of the transmitted light is not very different for the dilute solutions and for the stronger ones. The explanation for this feature is chiefly that in neither case does the yellow sector of the spectrum in the range of wavelengths between 570 and 590 $m\mu$ appear in the transmitted light. Indeed, the bands of transmission in the green and in the red come close to each other but the intervening yellow is scarcely visible. In the absence of the yellow sector, the transmission of the red sector has but little influence on the perceived colour. The only perceivable change is a diminution in the fullness or degree of saturation of the colour.

That the green solutions of chromium chloride powerfully absorb the yellow sector of the spectrum is strikingly illustrated by viewing a brightly illuminated screen through a cell containing such a solution and then suddenly removing the cell. The fovea of the observer's retina is then conspicuously visible projected on the screen as a bright yellow disk.

Solutions of methyl violet: Using a glass cell 2 cm deep containing distilled water, and adding to it drop by drop a strong solution of the well-known dye-stuff methyl violet, the changes resulting therefrom in the perceived colour of the transmitted light and their relation to the changes in its spectral character can both be followed step by step. The first noticeable change in the spectrum of the transmitted light is the manifestation of a powerful absorption in the wavelength range from 570 to 600 $m\mu$. This becomes more and more pronounced and finally quite complete. Accompanying this change and evidently as the result of it, the transmitted light assumes a reddish-purple colour and this develops into a fully saturated hue. On further addition of the methyl violet, the absorption of the yellow extends into the orange up to about 620 $m\mu$. A weak and rather ill-defined absorption also appears in the spectral range between 520 and 570 $m\mu$. This ultimately joins up with the absorption in the yellow and orange and forms a continuous band of extinction extending from about 520 to 620 $m\mu$. The final colour of the transmitted light is a reddish-purple, not noticeably different from that exhibited when the absorption of the green is weak and just noticeable.

The facts of observations stated above clearly indicate that it is the absorption of the yellow in the spectrum by the dye-stuff which results in the manifestation of a reddish-purple colour by its solution.

Solutions of crystal violet: Following the same procedure as that described above for the case of methyl violet, the behaviour of solutions of the closely related dye-stuff crystal violet can be studied. The detailed description of the observed effects given above may be repeated almost *verbatim*, except for the following differences. The strong absorption which first manifests itself now extends from 580 to 610 $m\mu$ instead of from 570 to 600 $m\mu$ as in the case of methyl violet and the colour of the transmitted light is a bluish-purple instead of a reddish-purple. The extinction band which is seen when a sufficient quantity of the dye-stuff has been added to

the solution now extends from 530 to 630 $m\mu$, and the colour of the transmitted light at this stage remains a bluish-purple.

Thus, the facts indicate that it is the absorption of the yellow in the spectrum by the dye-stuff which results in the manifestation of a bluish-purple colour by its solutions. That methyl violet yields reddish-purple solutions while crystal-violet yields solutions of a bluish-purple colour becomes intelligible when it is mentioned that the brightness of the red sector relatively to the blue sector as perceived in the spectrum of the transmitted light is manifestly greater for methyl violet than for crystal violet.

Solutions of bromo-cresol purple: An intense absorption of the yellow in the spectrum is a characteristic property of aqueous solutions of this dye-stuff. Dilute solutions of it exhibit a purple colour and spectroscopic examination of the transmitted light reveals that this is a consequence of the powerful absorption appearing as a dark band in the spectrum covering the spectral range from 570 to 610 $m\mu$, while there is no noticeable absorption of either shorter or longer wavelengths. With further addition of the dye-stuff to the solution, the absorption band spreads in either direction, and covers the spectral range from 550 to 620 $m\mu$. No noticeable change in the colour of the transmitted light however results therefrom.

Solutions of bromo-phenol blue: Dilute solutions of this dye-stuff exhibit a light bluish-purple colour associated with an intense absorption covering the spectral range from 580 to 610 $m\mu$ and perfect transparency to the rest of the spectrum. Less dilute solutions exhibit a somewhat deeper purple colour coupled with an absorption covering the spectral range from 550 to 620 $m\mu$.

Solutions of chloro-phenol red: Dilute solutions of this dye-stuff exhibit a powerful absorption in the wavelength range 560 to 590 $m\mu$ which appears as a dark band in the spectrum. The colour of the solution as exhibited by a layer 2 cm thick is a purplish red. Less dilute solutions exhibit an absorption band covering the wider spectral range from 540 to 600 $m\mu$ and the same colour but somewhat more pronounced. There is also a distinct general absorption of the blue and the green in the spectrum and consequent weakening of those regions. This is evident on a comparison with the red part of the spectrum.

Solutions of coomassie violet: When a few drops of a solution of this dye-stuff are put into a cell containing distilled water, the spectrum of the transmitted light exhibits a weak absorption in the wavelength range between 500 and 560 $m\mu$, in other words of the green sector in the spectrum. Further additions increase the strength of this absorption till it becomes complete and appears as a dark band crossing the spectrum. There is, however, no noticeable spreading out of the band, nor is there any noticeable absorption in the other parts of the visible

spectrum. The colour of the very dilute solutions is a pale rose red, and this deepens and becomes a bright rose red when the absorption in the green is complete.

Solutions of magenta: Very dilute aqueous solutions of this dye-stuff exhibit a well-defined absorption band covering the spectral range from 540 to 560 $m\mu$ in the green, while the colour of the transmitted light is a rose-red. Further additions of the dye-stuff result in this band extending up to 590 $m\mu$, and also in a general absorption which weakens the transmission of the blue and green of the spectrum. The colour of the transmitted light then turns to a brilliant red.

Solutions of methul blue: This dye-stuff exhibits a powerful absorption in the wavelength range 650 to 680 $m\mu$ which appears as a dark band crossing the spectrum of very dilute solutions. With successive additions of the dye-stuff this absorption spreads out in both directions. The transmitted light exhibits a full blue colour when the cut-off of the shorter wavelength extends up to 570 $m\mu$, despite the fact that the green sector then appears with undiminished intensity along with the blue and there is also an observable transmission at the extreme red end of the spectrum. Further additions of the dye-stuff which shift the position of the cut-off to 550 $m\mu$ reduce the observed intensity of the transmitted light but have no noticeable effect on its colour.

Solutions of methyl green: Despite its name, a fairly strong solution of this dye-stuff in a cell 2 cm thick appears of a full blue colour, the spectrum of the transmitted light covering the wavelength range from 450 to 550 $m\mu$, besides a narrow band in the red at 700 $m\mu$; the intermediate region from 550 to 700 $m\mu$ exhibits a practically complete absorption. Dilution results in the absorption band becoming narrower, then covering the wavelength range from 570 to 680 $m\mu$; and the transmission of the blue then extends to 440 $m\mu$. In these circumstances, the green of the spectrum appears with full strength in the transmitted light; nevertheless, the perceived colour remains blue. Not until the dilution is carried much further and there is free transmission up to 590 $m\mu$, does the colour change to a light greenish-blue.

Results of the study: We now proceed to state the conclusions which follow from the observations set forth above. The major result which emerges from the studies made with a variety of materials differing widely in their chromatic behaviour is the immense importance of the role played by the yellow sector of the spectrum and in particular, by the wavelength range between 570 and 590 $m\mu$, in the perception of light and colour. The presence or absence of this range of wavelengths in the light received by the eye of the observer makes all the difference to the visual impressions produced by it.

First of all, we may refer to the most surprising result of all, viz., that the

removal of the yellow sector from white light, other things remaining the same, results in producing the colour sensation familiarly known as purple. Numerous examples of this finding have been set out above. Many further illustrations that emerge from the studies of floral colour and of the hues exhibited by various natural and synthetic products will form the subject of later chapters.

If in the composite light under observation, the blue sector is stronger relatively to the red sector than is normally the case while the yellow sector is absent, the colour sensation would be a bluish-purple. The weaker the red sector is, the more nearly would the bluish-purple resemble blue in its characters. If the situation is reversed and the red sector is stronger relatively to the blue than it is normally, the colour perceived is a reddish-purple, tending more and more to resemble red in the limiting case when the blue is very weak.

More generally, the studies indicate that the presence in full strength of the part of the spectrum lying within the wavelength range 560 to 600 $m\mu$ is incompatible with the excitation by composite light of the highly chromatic sensations described by the terms blue, green or red. Only in the absence of the yellow sector of the spectrum can these colours be perceived at all, or at least without being modified to such an extent as to be unrecognisable.

The studies also furnish evidence of the existence of a physiological phenomenon which may be conveniently termed as the masking of one colour by another. An effect of this nature very clearly manifests itself when the composite light includes both the parts of the spectrum which we have referred to as the blue sector and the green sector. When the spectrum of white light is visually observed either through a prismatic spectroscope or through a diffraction grating, the green of the spectrum between 500 and 560 $m\mu$ appears far more luminous than the part of the spectrum between 400 and 500 $m\mu$. Nevertheless the light transmitted by a filter which passes both of these regions freely but cuts out the light of greater wavelength appears of a blue colour without any indication appearing of its admixture with green light.

The new physiology of vision—Chapter XIX. Perception of colour and the trichromatic hypothesis

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The colouring of textiles with the aid of dye-stuffs is an art of great antiquity. The availability at the present time of synthetic dyes of varied sorts has greatly enlarged the range of the colours which can be fixed on textile fibres. In consequence, the student who wishes to study dyed textiles has at his disposal sufficient material with which the entire field of colour could be covered. The present chapter records some observations made by the author on dyed silks with a view to determine the relationship between their perceived colours and the spectral character of the light which emerges from the material after escaping absorption in its interior. As the particular dye-stuff employed in the case of each specimen was unknown, the observations have been set out in the order of the colours exhibited by the materials studied. These observations were intended to supplement those described in the preceding chapter in which the spectral character of the light transmitted by various colour filters was studied in relation to its perceived colour. The results were there set out separately for each of the materials used as a filter. They and the results obtained and reported here using a wholly different technique have been found to be completely in agreement.

The picture of the relationship between the perceived colour of polychromatic light and its spectral character which emerges from these studies bears no resemblance whatever to that envisaged by the so-called trichromatic theory of colour perception. It follows that the ideas underlying that theory are unsustainable. This aspect of the matter will be dealt with more fully as we proceed.

The sensation of purple: The purple dye with which the togas of the Roman Emperors were tinted was a very expensive material derived from a kind of shell-fish. A purple colour can however be readily produced with the aid of synthetic dyes. Indeed, purple silk is not infrequently adopted as the material for academic costumes. The author has in his possession, three such costumes acquired at widely different dates. One is a full gown of purple silk, another a gown and hood of scarlet-coloured wool with facings of purple silk, and a third is a gown and hood of scarlet silk, with the addition of an academic cap of a dark purple velvet with an inside lining and an outer edging of purple silk. The three samples of purple

silk present somewhat different shades of colour. But on a spectroscopic examination, all showed in a very conspicuous fashion a common feature, viz., that while the red, green and blue sectors in the spectrum were present in strength, the yellow of the spectrum was totally absent. There is a large drop in intensity between the green and the red sectors, the minimum being located at about $590\text{ m}\mu$. The purple silk edging in the third sample showed a well-defined dark band in the spectrum covering the spectral range between 580 and $610\text{ m}\mu$.

The luminosity of the red sector relatively to those of the blue and green sectors varied as between the three samples. The full gown of purple silk which showed a violet shade of colour showed the blue sector of the spectrum more brilliantly than the other two. *Per contra*, the purple silk of the third sample which exhibited a distinctly red shade of colour, exhibited the red sector rather more conspicuously in its spectrum. In every case, the green sector of the spectrum was conspicuous and was more luminous than the blue sector.

The behaviour of the three samples of purple-coloured silk demonstrates conclusively that the purple sensation has its origin in the suppression of the yellow sector of the spectrum by its absorption in the material, the blue, green and red sector continuing to be present in full strength, this being about the same in relation to each other as in white light. Deviations of the red-blue ratio from the normal value result in the exhibition of different shades of purple. We have here a clear contradiction with the ideas regarding colour embodied in the trichromatic theory of colour perception. According to that theory, the purple sensation is complementary to the green and arises from its absence. In other words, the more fully the green sector of the spectrum is extinguished, the deeper or more fully saturated would be the resulting purple sensation. So far from this being actually the case, we find that a fully saturated purple sensation is perceived despite the presence with undiminished intensity of the green sector in the spectrum of the light issuing from the material.

The sensation of blue: Spectroscopic examination of a sample of blue silk showed a complete extinction of the yellow region in its spectrum. This extinction manifested itself as a dark band covering the wavelength range from 560 to $590\text{ m}\mu$. The red sector of the spectrum also exhibited a notable diminution of brightness, as also a dark band crossing the spectrum and covering the spectral range from 620 to $650\text{ m}\mu$. Despite these manifestations of absorption in it, the red sector of the spectrum was very far indeed from total extinction. The green sector of the spectrum in the wavelength range from 500 to $560\text{ m}\mu$ was also conspicuous. Though the blue sector showed an enhancement relatively to the green as compared with what is observed with white light, nevertheless, the green sector of the spectrum as seen through the instrument was not less luminous than the blue.

Numerous other examples of blue silk were examined spectroscopically. In all cases, the yellow of the spectrum was powerfully absorbed and indeed except in

the case of one sample which was of a light blue colour, it was quite inconspicuous. The red of the spectrum was also much weakened but never actually extinguished. The brightness of the green sector relatively to that of the blue sector varied from specimen to specimen. It could be stated as a general rule that the deeper the colour of the silk, in other words, the more nearly it approaches an indigo colour, the less was the intensity of the green sector relatively to that of the blue.

It is evident from these studies that an elimination, more or less complete, of the yellow sector of the spectrum is essential for the perception of a blue colour. Equally essential is a substantial reduction in the luminosity of the red sector. The part played by the green sector is less obvious. That a saturated blue colour is observed even though the green and red are conspicuously present in the spectrum can scarcely be reconciled with the assumption that the sensory impressions produced by polychromatic radiation represent a simple summation of the visual sensations excited by the different parts of it. Indeed, what we actually observe may be described as masking of the visual sensations excited by the red and green sectors by that of the blue sector. It has, however, to be recognised that the progressive elimination of the green sector by absorption results in the observed blue colour assuming a deeper hue.

The sensation of red: A bright red colour frequently appears in the gorgeously coloured silk sarees for which Bangalore is famous. It was, therefore, possible for the author to examine numerous specimens of red silk spectroscopically. They all exhibited a remarkable effect, viz., a dark absorption band covering the yellow of the spectrum and separating the red from the adjoining green in the spectrum. If the absorption band is absent, the colour of the silk is not red but either scarlet or orange as the case may be, depending on the proportion of yellow light escaping from the material. If, on the other hand, the absorption extends towards greater wavelengths, the colour of the silk is a darker red.

It is evident from these observations that the extinction of the yellow in the spectrum is an essential requisite for the material to exhibit a red colour. But what is particularly remarkable is that all the specimens examined exhibit the green and blue sectors in their spectra though with enfeebled intensity. It would appear in these cases the sensation excited by the red sector of the spectrum results in a masking of the effects of the green and blue sectors by reason of their lower intensities.

The sensation of green: Silk which has been dyed green exhibits a whole range of colours varying from what may be described as a light green at one end to a deep green at the other. Spectroscopic examination reveals that the appearance of even a light shade of green is accompanied by a weakening of both the blue and red sectors of the spectrum. Noticeable also is a fall in brightness of the range of wavelengths between 560 and 600 m μ relatively to the wavelength range between

500 and 560 $m\mu$, in consequence of which the maximum of luminosity in the spectrum shifts visibly towards smaller wavelengths. These features are all accentuated in the case of the specimens exhibiting deeper colours, so much so that silk which appears a full green shows a nearly complete extinction of the yellow of the spectrum and the maximum of luminosity appears at 530 $m\mu$. Silk which is of a deep green colour exhibits the maximum of luminosity at 525 $m\mu$ and the fall of the luminosity with increasing wavelength beyond 550 $m\mu$ is so marked that a dark band separating the green and the red in the spectrum is clearly recognisable. The blue of the spectrum is very weak and may be perceived extending beyond the green towards shorter wavelengths. The red of the spectrum is also weakened but remains a conspicuous feature in the spectrum of even the darkest green silk. But it does not exert any observable influence on the perceived colour.

We may sum up by stating that an extinction of the yellow sector of the spectrum is essential for the material to exhibit a green colour. The red of the spectrum continues to be observable but is masked from perception by the more luminous green.

The blue-green sequence: Silk may be dyed so as to exhibit a whole range of colours which may be described as intermediates between green and blue. Spectroscopic examination reveals certain features common to the whole sequence and other features which exhibit a regular progression in the series. The common feature of the whole range of colours is a large fall in the brightness of the red sector as well as a practically complete extinction of the yellow sector. The progressive feature is the extension of the spectrum towards shorter wavelengths and the increase of the intensity of the blue sector. Remarkably enough, however, in all these cases, the green sector of the spectrum as observed through the instrument appears much more luminous than the blue.

Rose-coloured silk: Of exceptional interest is the case of dyed silk which exhibits a rose-red hue which is both brilliant and attractive. Spectroscopic examination reveals that this colour has its origin in an extinction of the green sector of the spectrum, while the rest of the spectrum including especially the blue sector, remains of undiminished intensity. That the colour resulting from this extinction of the green of the spectrum is a brilliant rose-red is a particularly significant fact. It presents us with a clear-cut contradiction of the ideas of the trichromatic theory according to which the sensation resulting from a suppression of the green in the spectrum should have been a highly saturated purple.

The theory of colour perception: The facts of observations set out above and in the preceding chapters enable us to form fairly clear ideas regarding the nature of the relationship which exists between the spectral character of polychromatic radiation and its perceived colour. It is also possible to go further and to venture

upon an interpretation of the facts, basing ourself on a recognition of the corpuscular nature of light and the part that it plays in the perception of the colours of monochromatic radiation.

The spectrum of white light presents to our vision a continuous progression of colour in which we can distinguish a great many different hues. At some points in the spectrum, the progression of colour is exceptionally rapid and at others it is relatively slow. These experiences become intelligible when it is recalled that the energy associated with a light corpuscle increases progressively from one end of the spectrum to the other and that the perception of light arises from the absorption of the energy of the corpuscle and its transformation in the retina into the energy of electrical impulses which travel to the centres of perception. The variations of the luminous efficiency of radiation and of the power of colour discrimination in the spectrum arise as consequences of the spectroscopic behaviour of the visual pigments in the retina. Further, each different colour which we can perceive in the spectrum is "a fundamental visual sensation" and can claim recognition as such equally with every other colour in the spectrum.

It is the conjoint effect of the sensations excited by all individual parts of the spectrum of polychromatic radiation that determines its colour. By reason of the varying luminous efficiency of radiation in the spectrum, these individual contributions differ greatly, apart from the variations determined by the varying absorption in the material. Some sections in the spectrum may therefore be expected to contribute to the visual effect much more than others. In earlier chapters, factual evidence has been presented that the major visual sensations are those associated with the yellow sector of the spectrum. It is therefore not at all surprising and indeed could have been confidently anticipated that the removal of the yellow sector from the spectrum would result in notable chromatic effects and that the presence or absence of that sector would be the principal determining factor for the observed colour of the light. This, indeed, is what we actually find to be the case.

It is convenient in considering the colour sensations excited by polychromatic radiation to consider its spectrum to consist of four sectors: the blue sector from 400 to 500 $m\mu$; the green sector from 500 to 560 $m\mu$; the yellow sector from 560 to 600 $m\mu$ and the red sector from 600 to 700 $m\mu$. We may ask ourself, what would be the result of removing the yellow sector from the spectrum of white light, other things remaining the same. We have the blue and green sectors on one side and the red sector on the other side. What observation tells us is that the result is a purple sensation. We can therefore identify this sensation as the result of the superposition of the blue, green and red sectors, the yellow sector being absent. Observation likewise tells us that when the red is also weakened, even if it is not actually extinguished, the sensation perceived is blue. In other words, the observed sensation changes from purple to blue if the balance is tilted towards shorter wavelengths by lowering the intensity of greater wavelengths. If, further, the blue sector is much weakened, the sensation perceived is green, even though

the red has not been totally extinguished. Thus, in every case, it would be seen that the perception of colour is determined by the domination or masking of the weaker by the stronger sensations. It is also evident from the facts that the blue and the green sectors are not antagonistic to each other, the perceived sensation arising from their co-operation being a blue or a green or an intermediate colour, according to the circumstances of the case. Other examples of transitional colours present themselves in the sequence of hues ranging from a pure yellow to a pure red through the intermediates of an orange yellow, an orange and a scarlet.

The trichromatic hypothesis: From the theoretical standpoint, each of the numerous distinguishable colours we can perceive in the spectrum is an independent visual sensation. The trichromatic theory of colours bases itself on the idea that the perceived colours of polychromatic radiation can be described in terms of "three fundamental sensations" and that these may be summed up making use of a set of empirically determined coefficients (positive or negative as the case may be) which vary from point to point over the spectrum. That the procedure is highly artificial is obvious, and its claim to acceptance disappears when the basic idea and its consequences are found to be flatly contradicted by the facts of observation. As we have seen, the circumstances in which polychromatic radiation actually presents itself to our perceptions as exhibiting such readily recognisable colours as purple, blue, green and red are very different from those contemplated by the trichromatic hypothesis.

One of the reasons for this failure of the trichromatic hypothesis stands out clearly. That hypothesis regards red, green and blue as the major visual sensations and relegates the sensation of yellow to a minor and secondary or derivative position. Actually, it is yellow which is the major visual sensation, while the red, green and blue though more colourful are only its subsidiaries. They are perceived as full colours only when the yellow is put out of the way.

The new physiology of vision—Chapter XX. Superposition and masking of colours

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The following questions of a fundamental nature arise in the theory of colour. If two beams of monochromatic light of different colours are perceived by our eyes simultaneously, what would be the resulting sensation and how would it depend on the relative brightness of the two beams? An answer to these questions is needed for every possible pair of colours in the spectrum. If it is forthcoming, it would furnish material for a fuller understanding of the phenomena we are confronted with in the synthesis of colour, a subject which has been dealt with in the two preceding chapters. Observational studies are necessary which would enable the questions raised above to be answered. They will be described and the results obtained will be discussed in the present chapter.

The method of superposed spectra: A very simple technique by which the effect of superposing monochromatic light from two different parts of the spectrum can be ascertained is to use two linear light sources held parallel to each other and for the observer to view the diffraction spectra of the two sources simultaneously with a replica grating held in front of his eye. The two sources may be two similar lamps or two illuminated slits held at a convenient distance apart which can be varied as desired. The first-order diffraction spectra of the two sources are then seen superposed but in displaced positions with respect to each other. If one of the sources is placed at a slightly higher elevation than the other, the superposition is effective over the greater part of the width of the two spectra, but a little of each spectrum would project beyond the other, thereby enabling the observer to notice the two colours which are superposed at any point in his field of view. By appropriate methods, viz., by varying the electric current through the tubular lamps or by varying the width of the illuminated slits, the relative brightness of the two sources can be altered. By changing the separation between the two sources or by the observer moving towards or away from them, the displacement of the spectra with respect to each other can be varied to any desired extent. The colours seen in the overlapping parts of the two spectra can then be readily compared with those in the non-overlapping regions.

Observations made in the manner described make it evident that the visible

spectrum extending over the range of wavelengths from 7000 to 4000 A.U. falls into two divisions. The first division from 7000 to 5000 A.U. covers the red, yellow and green sectors of the spectrum, while the second division from 5000 to 4000 A.U. is the blue sector, including in this term the regions where blue, indigo and violet are observed either in different parts or at different levels of brightness, as the case may be. Each of these two divisions of the spectrum has the property that any two monochromatic radiations selected from different parts of it when superposed result in a chromatic sensation of the same nature as is to be found within that division, its position, however, being dependent on the relative brightness of the two superposed radiations. If, for example, we superpose monochromatic light which exhibits a red colour upon another which appears green, the resultant would be one or another of the intermediate colours in the spectrum, the position of which would be determined by the relative intensity of the two superposed radiations as indicated by the formula:

$$n_1 h\nu_1 + n_2 h\nu_2 = (n_1 + n_2) h\nu_3.$$

The formula states that the energy as well as the number of corpuscles perceived is a summation of their respective values for the superposed radiations. It follows from this assumption that the resultant would be perceived as light of frequency ν_3 which is intermediate between ν_1 and ν_2 and is nearer one or the other according as n_1 is greater or less than n_2 . The formula assumes that the more intense radiation does not mask the weaker radiation thereby preventing its influence being felt in the final result. There is observational evidence, however, that such masking does occur when one of the superposed radiations is much more intense than the other.

The reason why the spectrum falls into two chromatic divisions in the manner indicated above is not far to seek. In the first division, as has been set out in earlier chapters, the visual pigments are chemically of the same nature, viz., heme, but in different states of oxidation and their absorption spectra overlap. In these circumstances, it is to be expected that they would co-operate in the reception of polychromatic radiation and enable it to be perceived as a monochromatic sensation. The position is entirely different when the radiations which are superposed belong to the two different divisions of the spectrum. The visual pigment in the second division is of a different nature, viz., a carotenoid. Further, the two divisions of the spectrum represent light-corpuscles of widely different energies. It could scarcely be expected in these circumstances that the chromatic sensations associated with monochromatic radiations from the two different divisions should be coherent and be perceived as a single monochromatic sensation.

The foregoing remarks indicate that the superposition of a monochromatic radiation selected from the blue sector of the spectrum upon a radiation selected from the red, yellow or green sector would result in the production of colour sensations of a distinctive character. This is found to be actually the case when the

matter is investigated by the method of superposed spectra described above. As the blue sector of one spectrum successfully traverses the red, yellow and green sectors of the other spectrum, beautiful and striking changes are noticeable in the colours of the superposed spectra, the colours observed being quite different from the monochromatic sensations which are superposed on each other. We shall later return to a detailed description of these effects. Presently, we shall proceed to consider from first principles the phenomena which may be expected to manifest themselves in such cases.

Theoretical considerations: The most natural assumption to make regarding the sensation excited by two monochromatic radiations of widely different frequencies ν_1 and ν_2 when superposed is that it can be represented by a formula of the type

$$n_1 h \nu_1 + n_2 h \nu_2 = n_1 h \nu_3 + n_2 h \nu_4.$$

The formula assumes that both the energy and the number of light-corpuscles perceived when the radiations are superposed is a simple summation of these quantities for the two radiations considered separately. It is postulated, however, that the superposition can result in an alteration of the frequencies of the perceived radiations. The equation contains two unknowns, viz., ν_3 and ν_4 , with only one equation connecting them. It follows that the values of ν_3 and ν_4 are not exactly definable, but that they can range over wide tracts in the spectrum. If the ranges of variation of ν_3 and ν_4 are sufficiently large to cover the entire visible spectrum, the resulting sensation would be more or less perfectly achromatic, in other words, it would resemble white light. Whether this result actually manifests itself would depend on the particular circumstances of the case. Of special importance in this respect would be the relative intensity of the two superposed beams. If for example, n_1 is very large compared with n_2 , the resultant sensation would evidently approach the monochromatic colour of ν_1 . Vice-versa, if n_2 is large compared with n_1 , the perceived sensation would resemble the colour of ν_2 . More generally, however, the sensation would resemble neither the one nor the other and would largely be determined by the continuous spectrum of perceived frequencies.

The considerations set forth above give us an intelligible explanation of a well-known fact of experience, viz., the existence of what are known as complementary colours in the visible spectrum. The complementarity manifests itself as between two regions in the spectrum widely separated from each other, one in the region between 700 and 560 m μ , in other words, in the red and yellow sectors of the spectrum and the other in the blue sector of the spectrum between 500 and 400 m μ . If radiations suitably selected from these two regions and having the appropriate relative intensities are superposed, the resulting sensation is that of white light. Such complementarity is exhibited when the two superposed beams have comparable luminosities, if one of them is located in the orange-yellow at

about $600\text{ m}\mu$ and the other in the blue-green region at about $490\text{ m}\mu$. In these circumstances, it would evidently be possible for the spread-out of the perceived frequencies of the two components to result in the entire visible spectrum being covered, and hence to result in the perception of an achromatic sensation.

Confirmatory observations: A convincing demonstration can be given that the process envisaged in the preceding theoretical discussion actually occurs, viz., that the superposition of two monochromatic radiations of widely different frequencies results in each of them being perceived spread out into a spectral band of frequencies. For this purpose, two highly monochromatic light-sources of which the colours are far apart in the spectrum may be selected. A suitable choice for one is the violet $\lambda 4358$ radiation from a mercury vapour lamp. This may be readily isolated from its other radiations by using a fairly strong solution of cuprammonium as a light filter. For the other, a suitable choice is the orange-yellow light of wavelengths $\lambda 5890\text{--}5896$ furnished by a sodium vapour lamp. Light from these two sources may be projected with the aid of apertures and lenses to appear as luminous circles on a white screen. The region where the two circles overlap is observed to exhibit a vivid rose-red colour, in striking contrast with the violet and orange-yellow colours of the non-overlapping regions.

As has been shown by several examples in earlier chapters, a rose-red colour results from the removal of the green sector ranging from 500 to $560\text{ m}\mu$ from white light, while the rest of the spectrum including especially the blue sector from 400 to $500\text{ m}\mu$ remains of undiminished brightness. Thus, what is actually observed in the experiment indicates that the superposition of the violet and orange-yellow radiations has resulted in the former being perceived as a spectral band covering the blue sector and of the latter being perceived as a spectral band covering the red and yellow sectors of the spectrum. This interpretation of what is observed receives confirmation from the observed result of projecting on the same screen, the $\lambda 5461$ radiations of another mercury arc isolated with the aid of colour filters of disulphine-blue and acridene-orange. Where the circle of green light thus obtained overlaps the rose-red region, the area appears achromatic. On the other hand, in the region of overlap of the green and violet, the perceived colour is a pale bluish-white. Where the green circle overlaps the circle of orange-yellow light, we perceive a bright lemon-yellow colour.

In the experiment described above, we may use, instead of the orange-yellow light from a sodium lamp, red light from the extreme end of the spectrum at $700\text{ m}\mu$ which may be isolated from white light by passing it through a dense filter of methyl-violet and another filter of acridene-orange. It is then noticed that where the circle of red light obtained in this fashion overlaps the circle of violet light from the mercury lamp, the colour observed in the region is *not a purple* but a rose-red similar to that obtained by the superposition of orange-yellow and violet. Likewise, in the present case, the rose-red colour of the region of overlap

may be achromatised by the superposition of green light isolated from the radiations of a mercury lamp.

A similar experiment may also be performed using the violet $\lambda 4358$ radiation from one mercury lamp and the yellow $\lambda 5770-5790$ radiations from another mercury lamp isolated with the aid of colour filters of eosine and acridene-orange. When the circles of violet and yellow light thus obtained are projected on a white screen, the region of their overlap appears of a rose-red colour. But this does not present such a saturated hue as in the other cases.

The colours in superposed spectra: We now return to the subject of the colour sequences observed when two diffraction spectra are superposed upon each other in displaced positions as in the manner explained earlier. This technique is particularly useful in the study of colour superposition, since it enables us to observe the entire region of overlap between the spectra at a glance and to compare the colours noticeable at different points in the region and also to observe how they alter as the spectra are progressively displaced with respect to each other. The influence of varying the relative intensities of the two spectra can be very conveniently studied.

Of particular significance and interest is the fact that the boundary at about $500\text{ m}\mu$ between the green and the blue in the individual spectra manifests itself as a highly pronounced discontinuity in colour in the overlapping regions of the two spectra. Extremely conspicuous, for example, is this discontinuity when the blue sector of one spectrum overlaps the orange-red, orange and orange-yellow regions in the other spectrum. The overlapping region appears as a brilliant rose-red band of colour with a sharply defined edge on one side corresponding to the green-blue boundary of the first spectrum. The colour changes sharply from a rose-red to a bright greenish-yellow at the boundary. On the other side of the rose-red band, one can observe a narrow region of the spectrum which is nearly achromatic and corresponds to the point where the yellow of the second spectrum overlaps the blue of the first.

The discontinuity in the colour sequence persists when the two spectra are displaced with respect to each other from the position stated above, but the colours observed on either side of it are naturally then different. If, for example, the blue sector of one spectrum overlaps the green sector of the second, the region of such overlaps appears of a bluish-white colour, sharply differentiated from the orange-yellow on the other side of the discontinuity arising from the overlap of the green sector of the first spectrum with the red sector of the second.

The new physiology of vision—Chapter XXI. The green colour of vegetation

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In the present chapter and the following one, we shall concern ourselves with the products of the plant world which are available in great variety as materials for a study of the relationships between the sensory perception of colour and the spectral characteristics of the light which is perceived. The nature of these relationships has already been ascertained from the observations described in earlier chapters. But the illustrations of the same which are furnished by studies of floral colour are particularly striking and impressive.

The most familiar of all plant colours is the characteristic green colour of foliage. The immensely important role played by the green leaves of plants in photosynthetic activity is well-known. It is the absorption of light by the pigments present in the green leaves which enables them to play this role and it is the same pigments which determine the spectral character of the unabsorbed light emerging from the leaves on which depends their perceived colour. It is this relationship that invests the study of the colour of green leaves with special interest and importance.

Massed display of colour: We may appropriately begin with a reference to the circumstances which enable vegetation to display the colours with which we are all familiar. It is a characteristic feature of foliage that the two sides of each leaf present a different appearance, the difference in some cases being highly pronounced. One side of the leaf is smooth and exhibits vivid colour, while the other side has a rough surface and a dull colour. Invariably, however, the side which is smooth and vividly coloured is turned towards the light, thereby enabling the photosynthetic activity of the leaf to function. Further, the outermost leaves screen the interior of the plant or tree from observation. As the result, a mass of foliage from whatever direction it may be viewed exhibits the most brilliant display of colour which it is capable of. This feature of plant life contributes much to its attractiveness and explains why well-kept lawns, ivy-clad walls and trimmed hedges are much admired and extensively made use of around homes and in gardens. Indeed, the colour of vegetation is particularly impressive when seen from a distance where the individual leaves cannot be perceived. One

may here recall the magnificent spectacle provided by a great stretch of rice-fields in deltaic areas. It is also worthy of mention that we can recognise even distant trees by the distinctive colour of their foliage.

The development of colour: A special feature of interest which calls for explanation is the changing colour of vegetation which accompanies the growth and development of the leaves to full maturity. This is particularly obvious in the case of trees which drop all their leaves at a particular season of the year and begin again with a fresh suit of leaves when the season is propitious for their appearance and growth. But the same phenomenon can also be observed when new leaves are put forth on the growing stems of plants and trees. In general, the new leaves exhibit a greenish-yellow hue and this later alters to green and then progressively to darker shades of green. In some cases, the early leaves show other colours, appearing pink or even red; but these hues soon give place to the colours normally exhibited by foliage. Some reference should also be made here to the colours exhibited by leaves when the time arrives for them to drop off from the tree. The change commonly observed is from a dark green to a bright golden-yellow. But there are cases in which the leaves put on a bright red hue before they fall off. The display of such vivid colours by the foliage of trees before the onset of winter is a regularly recurring event in the colder climates of the world.

Spectroscopic studies: Even the thinnest of leaves is opaque to light in the sense that it is not possible to view distant objects through it. This is a consequence of the scattering of light in its passage through the leaf. But sufficient light diffuses even through the thickest of leaves to permit of its spectral character being ascertained with the aid of a pocket spectroscope. For this purpose, the leaf may be held against the bright sky or if necessary in the path of a beam of sunlight, the slit of the instrument being placed close to the leaf so as to prevent entry of extraneous light. Alternatively, the smoother side of the leaf may be viewed through the spectroscope, the light being incident directly on the surface under observation and emerging from inside the leaf after internal diffusion. In this method of examination, it is necessary to hold the leaf and view its surface at such an angle that the glitter due to reflection at the smooth surface of the leaf does not appear and vitiate the observations.

Very interesting results emerge from a comparative study of the leaves in different stages of growth from the same tree. For example, the mature leaves of the Jack-fruit tree (*Artocarpus integrifolia*) exhibit a dark green colour, while the small tender leaves are greenish-yellow, and three or four intermediate stages can be recognised between these extremes. The comparisons are best made by viewing the surface of each such leaf under similar conditions of illumination through the spectroscope, the leaf being held to the light at such an angle that the glitter due to the reflection at the surface is avoided. It is then noticed that despite the enormous differences in the colour of the leaf in various cases, the spectral range covered by

the light emerging from the leaf remains the same, viz., from 520 to 640 $m\mu$, these limits being set by the strong absorptions of the carotenoids and the chlorophylls respectively. The brightness of the spectrum shows a progressive diminution as we pass from stage to stage in the development of the leaf. But this cannot possibly account for the remarkable changes in colour.

A feature noticeable in the spectrum of the light emerging from the thinnest leaf is a perceptible weakening of the yellow region as compared with the green and the orange on either side of it. This feature is more conspicuous in the spectra observed with the leaves in the later stages of development. With the thickest of the leaves which exhibits a dark green colour, this feature is highly pronounced and a dark band can be seen in the spectrum in the region where the yellow should have appeared. This band appears as a clear demarcation between the two parts of the spectrum on either side of it. From these observations, it is manifest that the extinction of the yellow part of the spectrum is a requisite for the dark green colour to be exhibited by the leaves. In other words, the progressive change of colour that accompanies the development of the leaves is produced by the enhanced absorption of the yellow region of the spectrum by the leaf pigment.

The absorption of the yellow by the leaf pigments covers the wavelength range between 570 and 586 $m\mu$ and appears between the green on one side and the orange and red of the spectrum on the other side. These colours may be observed in the spectrum when light falling on one side of the leaf and emerging on the other side of it is examined spectroscopically. They are equally well seen with the other method of observation described above. The green is definitely brighter than the orange and the red in all cases. But the difference is not great in the case of the thinnest leaves. The green gains in brightness relatively to the orange and the red as we proceed to the later stages of development of the leaf. But even in the case of the thickest leaves exhibiting a dark green colour, the orange and red regions continue to be observable and they are by no means of negligible brightness in comparison with the green. Since in these cases they make no perceivable contribution to the observed colour, we conclude that they are masked or prevented from being so observed by the more luminous green in the spectrum.

It is worthy of note that though these observations are as a matter of convenience best made using individual leaves, the same phenomena are also noticed when the spectroscope is directed by an observer towards any distant mass of foliage. Differences in the spectra of the same nature as those described above with individual leaves are noticeable in such cases as well.

Absorption spectra of the leaf pigments: Long ago, it was discovered by Sir George Stokes that the green pigment of leaves is a mixture of substances. Subsequent investigations have shown that the principal components are of two kinds, viz., the carotenoids and the chlorophylls. Here, we are only concerned with the absorption of light by the mixture of pigments. Both the carotenoids and

the chlorophylls can be extracted from the green leaf by prolonged immersion in organic solvents, the most suitable and effective of them being acetone.

Placing the acetone extract of the leaf pigment in a flat glass cell, 2 cm thick, the colour as seen by transmitted light and its relation to the absorption spectrum of the solution can be readily ascertained. The colour can be seen by holding the cell against the sky or other extended source of light. To ascertain the nature of the absorption spectrum, the observer can hold the cell before his eyes together with a replica diffraction grating and view the first-order diffraction spectrum of the linear source of light provided by a tubular lamp with a straight tungsten filament stretched along its axis. Alternatively, the absorption spectrum can be viewed through a pocket spectroscope, and the positions of the absorption bands may be read on the wavelength scale provided in the eye-piece of the instrument.

A striking demonstration of colour changes entirely analogous to those exhibited by the leaves of plants in the course of their growth and development is possible with the acetone extracts of the leaf pigments. The glass cell is filled to about a third of its depth with acetone and then the acetone extract of the leaf pigments (which is itself of a deep green colour) is added a little at the time. The acetone in the cell first turns yellow in colour. Further additions alter the yellow to a greenish-yellow and then progressively to a clear green. These changes correspond to the alterations in the character of the absorption spectrum of the solution. A cut-off of the red beyond $640\text{ m}\mu$ appears at the very outset, and this is soon followed by the total extinction of the blue up to $500\text{ m}\mu$. But not until the band of absorption in the yellow between 570 and $586\text{ m}\mu$ appears and is fully developed does the solution exhibit a full green colour.

Some finer details observed with the green leaves themselves correspond to the features noticed in the absorption spectra of the leaf extracts. Particular mention may be made of the two *bright* bands noticed in the spectrum of the leaves, one in the green between 550 and $570\text{ m}\mu$ and the other in the orange between 586 and $613\text{ m}\mu$. These bands are also noticeable in the spectrum of the transmitted light of the leaf-extracts.

The new physiology of vision—Chapter XXII. The colours of flowers

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It is appropriate that we commence this chapter by giving some indication of the magnitude of Nature's creative work as also of man's efforts to improve upon Nature in the production of floral colours. The best known of all flowers is the rose. No less than 421 names varieties of that flower are portrayed in full colour in the *Encyclopaedia of Roses* (Blandford Press, London) which the enterprise of the publishers has made available to rose-lovers. It is no exaggeration to state that the varieties of rose developed of recent years and pictured in that book exhibit a surpassing loveliness of form and colour. Useful service has also been rendered by the Oxford University Press by the publication of their two books on Wild Flowers and Garden Flowers respectively. 887 species are described in the first book and 635 species in the second, accompanied in each case by 191 full-page plates in colour. Finally, mention may also be made of the volume entitled *Some Beautiful Indian Trees* published by the Bombay Natural History Society, describing and illustrating in colour the spectacular beauty of several of India's best-known flowering trees.

From the publications referred to above, it is evident that the colours exhibited by flowers are many and of varied nature. What we are concerned with here is the role played by human vision in the synthesis of the spectral components of the light diffused by the petals of flowers which gives rise to the colour sensation actually perceived. In many cases there is no obvious relationship or resemblance between the sensation that is actually perceived and the physical characters of the light which reaches the eyes of an observer. This situation reveals itself when the observer proceeds to study the colours of flowers with the aid of a direct-vision spectroscope. A wavelength scale in the eye piece of the instrument is extremely helpful for fixing the location of the observed features in the spectra.

The technique for a study of the kind indicated above is essentially the same as that explained in the preceding chapter on the green colour of vegetation. As in the case of foliage, the petals of flowers often exhibit a difference in the appearance of their two faces. The face that exhibits the more vivid colour is held and viewed in diffuse light of sufficient brightness to permit of the examination of the spectral character of the light that enters the petal and emerges again after internal

diffusion. In the case of flowers there is usually no observable reflection of light by their petals which could interfere with the observations. But if such a reflection is noticeable in any case, it can be avoided by holding the petal at the proper angle to the light. The petal under observation has to be held at some little distance from the slit of the spectroscope which is directed towards it. It has, therefore, to be of adequate size and the observations are therefore made most easily with flowers having fairly large petals. However, even when the petals are small, if they are grouped together side by side in the flower, the spectroscope can be directed towards the aggregate, this being held facing the light at an appropriate distance from the instrument. Satisfactory observations are then possible.

There is an alternative procedure which can be adopted in all cases and is often found useful. The petal is held up against the light and close to the slit of the spectroscope, and the light that penetrates through it is viewed through the instrument. This is possible since in all cases, the flower petals are sufficiently thin to allow light to come through, though there is no regular transmission. A comparison between the characters of the spectra as observed with the two procedures is instructive. In many cases, there are differences in brightness and also noticeable differences in the spectral characters. These may arise in two different ways. Firstly, there is a difference in the absorption paths which are effective in the two cases. Secondly, in the observation of the light which has passed through the petal, both of its faces are effective in absorption and if there is any difference in the nature of the absorbing material present on the two sides, this would manifest itself in the spectrum of the light which emerges.

The fact that impresses itself forcibly on an observer who has made an extensive study of the material in the manner described above is the extremely important role played by the yellow sector of the spectrum, in other words, by the light included in the wavelength range from 560 to 600 $m\mu$ —in determining the perceived colours of flowers. In the preceding chapter, we have noticed that the foliage of plants does not exhibit its proper green colour unless the yellow of the spectrum has been more or less completely absorbed within the material of the leaves. The same phenomenon is even more conspicuously noticeable in respect of other colours. Indeed, it may be said that the presence or absence of the yellow sector in the light emerging from the petals of a flower makes all the difference in the colour which is perceived. No flower can exhibit a blue colour even feebly unless the yellow sector has been weakened by absorption and its place taken by a dark band crossing the spectrum. A vivid blue colour demands a complete extinction of the yellow sector and in addition a reduction in the intensity of the longer wavelengths in the spectrum. The removal of the yellow sector alone from the spectrum by absorption results in the colour of the flower being perceived as purple. But this may be modified so as more to resemble a red or a blue, if the red or the blue is stronger in relative intensity than in normally the case. Likewise, no flower can exhibit a proper red colour unless the yellow in its spectrum has been completely extinguished.

Classification of floral colours: The facts of observation set forth above suggest a basis for a classification of the whole range of observed floral colours. We proceed by specifying the part or parts of the spectrum in which the absorption by the pigments present in the flower-petals is effective. For this purpose, the spectrum is divided into four sectors, in the following order, viz., the blue, the green, the yellow and the red sectors, and their wavelength ranges are set respectively as from 400 to 500 $m\mu$, from 500 to 560 $m\mu$, from 560 to 600 $m\mu$ and from 600 to 700 $m\mu$. It is possible, of course, that the absorption actually exercised in any of these sectors may be only partial, and that it may not extend over the whole of the sector. However, for developing a scheme of classification, the actual situation may be idealised by making the assumption that there is either no absorption, or else a complete absorption of any particular sector. Considering these two alternatives and combining them for the four sectors, we have in all 16 different possibilities which may be listed by writing down 1 as the symbol for complete transmission and 0 as the symbol for complete absorption of each of the four sectors. Thus the list would commence from (1111) which would be the symbol for a white flower and end with (0000) which would indicate a flower which is totally black. When the absorption of a particular sector in the spectrum is only partial, the case may be fitted into the general scheme by placing it in the category which it most nearly resembles and indicating the extent to which the observed colour differs from that noticeable in the ideal case.

We may illustrate the scheme of classification suggested above by some actual examples. Yellow is a colour very commonly exhibited by flowers. Amongst flowering trees, the Indian laburnum (*Cassia fistula*) may be mentioned and also the well-known Copper Pod (*Peltophorum ferrugineum*), both of which are magnificent spectacles when in flower. Amongst garden flowers we may single out for special mention the gorgeous *Allamanda cathartica* which has huge bell-shaped waxy-yellow flowers which bloom all the year round. Spectroscopic examination reveals a complete extinction of the blue sector of the spectrum by its flowers, while the green, yellow and red sectors appear in full strength. Accordingly, this flower (and yellow flowers generally) would fall under the classification (0111).

Perhaps the most familiar example of orange-hued flowers in India is furnished by the magnificent sprays of flowers with which the climbing shrub *Bignonia venusta* covers the walls or screens over which it is allowed to grow up. The well-known aloe-wood tree *Cordia sebestena* also bears clusters of brilliant bell-like flowers of orange hue verging towards scarlet. Spectroscopic examination reveals a cut-off of the blue and green sectors of the spectrum while the yellow and red sectors are in full strength. Accordingly, orange flowers appear in the classification under the symbol (0011).

Amongst red flowers, one of the best known is the China Rose (*Hibiscus rosa sinensis*) which has large single bell-shaped blooms from which long bunches of stamens hang out. The petals exhibit a rich red hue. Spectroscopic examination

shows a complete extinction of the blue, green and yellow sectors in the spectrum, the red sector commencing from $600\text{ m}\mu$ being in full strength. Accordingly, red flowers may be classified as (0001).

If the absorption extends also into the red sector and covers wavelengths greater than $600\text{ m}\mu$, the colour of the flower would change from a bright red to a dark red or crimson and finally black. It would then belong to the category (0000). Such flowers could be regarded as intermediates between the categories (0001) and (0000). Likewise, those flowers in which the blue sector is absorbed in part while the green, yellow and red sectors are in full strength would exhibit a pale yellow colour. Such flowers may be regarded as intermediates between the categories (1111) and (0111). It is evident from what has been stated that the five categories (1111), (0111), (0011), (0001) and (0000) together with their intermediates would form a regular colour sequence in which a great many flowers would find a place.

Having dealt with the cases in which the blue sector of the spectrum is totally absent, we turn our attention to those in which the blue sector is present in full strength. There are eight categories of this kind which form two subgroups of four each, viz., (1111), (1110), (1100), (1000) and (1001), (1101), (1011), (1010).

Two items in the second subgroup are of particular interest, viz., (1101) in which the yellow sector alone is absent and (1011) in which the green sector alone is absent, while all the other sectors are present in full strength. As has already been stated, the absence of the yellow sector alone would result in a purple sensation, while the absence of the green sector alone would result in the perception of a bright rose-red hue. Remarkably enough, illustrations of both of these categories are furnished by the flowers of two distinct varieties of *Lagerstroemia flos reginae*, which is one of the most spectacular of Indian flowering trees. Its flowers appear in the months of April and May and are borne in great profusion from the ends of branches in large erect sprays. The tree is one mass of flower when it is in bloom. The petals of the flowers are six or seven in number and quite thin and crinkly, but they are nevertheless very colourful. Spectroscopic examination reveals a nearly complete extinction of the yellow sector in the case of the purple flowers, and of the green sector in the case of the rose-red flowers.

Blue flowers and their spectra: We may now usefully consider the class of colours represented by the symbols (1111), (1110), (1100), (1000) and (0000) together with their intermediates. These colours would be perceived if an absorption which commences at the long-wave end advances through the spectrum towards shorter wavelengths, covering up in succession the red, orange, yellow, green and then the blue, indigo and violet. The observed result would begin as white and end up as black. It is the step from (1110) to (1100), in other words, the extinction of the yellow sector of the spectrum which would be particularly significant, for a change of the perceived colour from white to blue would occur at this stage. The

preceding step, viz., the extinction of the red sector is, however, also important. For, the extinction of the yellow sector alone would give a purple sensation and not a blue.

All blue flowers exhibit in their spectra an absorption of the yellow sector. The more complete such absorption is, the more striking is the sensation of blue which results from its absence. In addition to the absorption of the yellow sector, the spectra of blue flowers also exhibit an absorption in the range of greater wavelengths. An absorption of the orange in the wavelength range between 600 and 630 $m\mu$ is particularly effective in this respect. This is to be expected, since the luminosity of the spectrum falls off rapidly at still greater wavelengths.

To illustrate how the perceived colour which arises from an absorption of the yellow and adjoining regions of the spectrum varies with the strength of such absorption, the flowers of the Morning Glory (*Ipomea learii*) and of the Heavenly Blue (*Thunbergia grandiflora*) may be compared with each other. Both are climbing plants which are great favourites as they produce large and showy flowers in striking colour contrast with the green foliage. The Morning Glory exhibits a saturated blue colour, whereas the Heavenly Blue presents a hue which is somewhat different and much less saturated. The spectra of the two flowers are strikingly different. The spectrum of the Morning Glory exhibits the entire visible spectrum from violet to red in full strength except in the wavelength range between 570 and 630 $m\mu$ which is strongly absorbed. The Heavenly Blue, on the other hand, exhibits rather weakly an absorption of the yellow between 570 and 590 $m\mu$ and also an absorption in the red around 630 $m\mu$. But the orange of the spectrum is not absorbed and is seen as a bright band with darker regions on either side. A dimming of intensity is also noticeable in the spectrum around 540 $m\mu$ in the green sector. It is worthy of remark that a spectrum very similar to that of *Thunbergia grandiflora* is exhibited by the flowers of *Jacaranda mimosifolia*, which is a spectacular tree bearing during the months of March to May an immense canopy of flowers and buds of a beautiful blue-violet colour.

Bougainvilleas: We shall now proceed to consider some individual cases presenting features of special interest. The Bougainvilleas form one of the most conspicuous and colourful features in Eastern gardens. They are very ornamental, grow vigorously in any soil with very little attention and can be adapted to various purposes. There are several natural varieties and numerous others have also been developed by horticulturists which present attractive colours. What appear to be its blooms are really the trios of brightly-coloured bracts which surround the true flowers.

One of the familiar varieties known as *B. rosa catallina* has very large rose-coloured bracts. Spectroscopic examination shows it to belong to category (1011), the green being strongly absorbed. There are also numerous varieties which exhibit different shades of purple. One may recognise amongst them a typical purple belonging to the category (1101) in which the yellow sector is

absent while the green is present in fair strength. Other varieties may be described as exhibiting a rose-purple colour and can be classed as intermediates between the categories (1011) and (1101). It is also possible to regard them as approximating to the category (1001) in which both the green and the yellow sectors have been extinguished by absorption. The varieties exhibiting a red colour show a complete extinction of the yellow sector which adjoins the red. But the spectroscope reveals that the green and the blue sectors are also present though with relatively low intensities.

The aster and its varied colours: The aster is well-known everywhere as one of the most showy of flowering shrubs. Each individual flower with its large feathery head and a gaily-coloured centre makes a most attractive picture. The asters commercially grown at Bangalore and exhibiting marked colour fall into two distinct classes. In each class one observes a progression of colour. In Class A the colour observed ranges from a bluish-purple to a deep violet. In Class B the colour observed ranges from a pale pink to a bright rose-red. A casual observer looking at the flowers might imagine that the asters of Class A absorb the longer wavelengths in the spectrum and therefore appear blue or violet, while the asters of the Class B absorb the shorter wavelengths and therefore appear red. Nothing could be further from the truth.

Spectroscopic examination reveals that the two classes are totally different in the nature of absorption which give rise to the perceived colours. The spectra in each class exhibit certain common features but there is a progressive change in the strength or intensity of the observed spectral features. The perceived colours of the asters in Class A have their origin in a readily observable extinction of the yellow sector in the spectrum. The absorption exhibits a well-defined edge at about $600\text{ m}\mu$, longer wavelengths having their normal intensities, while the absorption in the region of shorter wavelengths fall off progressively and becomes insensible at about $560\text{ m}\mu$. This absorption is moderately strong for the asters which appear purple-blue, quite strong for the asters which appear purple-violet and is total for those which appear of a violet colour. Apart from the strong absorption in the yellow, there are also indications of a minor absorption at $650\text{ m}\mu$ which results in the red sector of the spectrum appearing bifurcated. This is a feature which is just noticeable in the purple-blue asters. But it is more clearly seen in the spectra of the asters of a deeper colour, viz., those which appear of a violet hue.

The asters in Class B show a spectrum in which the violet, blue, yellow, orange and red sectors in the spectrum appear with their usual intensities, while in the green sector, there is a sensible weakening, especially between 530 and $560\text{ m}\mu$, the maximum of absorption appearing at about $545\text{ m}\mu$. This absorption is noticeable with the pink asters; it is quite strong with those which appear as bright pink, and nearly complete with the rose-red asters. It is evident from these facts of observation that the asters of Class A fall in the colour category (1101) and the asters of Class B in the category (1011).

The new physiology of vision—Chapter XXIII. The colours of the roses

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Roses have been known in India for ages past and have been highly esteemed for their beauty and fragrance. It is scarcely possible, therefore, to commence a paper on the colours of roses without some reference to the Indian rose known botanically as *Rosa indica semperflorence*. It is a shrub which is exceedingly vigorous in growth and flowers both freely and perpetually. The blooms are shapely, each having some forty petals. They appear as clusters at the end of tall canes growing up from the base of the shrub and are characterised by their soft pink colour and a sweet scent which perfumes the air around. These roses have been in extensive cultivation for various purposes, in particular for the production of the essential-oil perfume known as Attar. If groups of these shrubs are planted out in a garden, they make a very satisfying show of colour.

The reason why it appeared desirable to devote a whole chapter to the colours of roses is that the rose has long been a highly popular flower and enthusiastic rose-lovers are to be found all the world over. Interest in the rose continues unabated and thousands of varieties of it have been created by crossing and intercrossing the different species with each other. The colour of a rose forms a major part of its aesthetic appeal. Quite naturally, therefore, colour has been a decisive factor in the development, selection and propagation of new varieties. How far this activity has proceeded will be evident from *The Pocket Encyclopaedia of Roses* (1963), published by the Blandford Press in London. No fewer than 421 named varieties have been reproduced in full colour in that publication. It is stated that great care was taken to achieve a high degree of accuracy in the representation of the colours and to secure such accuracy, the illustrations were printed in six colours. Seeing these pictures, one may well ask, why do roses exhibit such colours and why do the different roses differ so markedly from each other? It is the purpose of this chapter to present answers to these questions.

The colour categories: The colour of a flower has its origin in the presence in its petals of a material which we may refer to as the floral pigment. This exercises an absorption on light which is of a selective nature, greater in some parts of the

visible spectrum and much less or even absent in other parts of it. As a consequence, diffuse daylight which is incident on the petals before it can emerge again from them after internal scattering has its spectral constitution much altered, some parts of the spectrum being weakened relatively to the others. When the light having this altered spectral character reaches the eyes of an observer, the characteristics of the visual mechanism determine the results of the visual synthesis and hence also the perceived colour. Thus, the colour exhibited by a rose is determined by our faculties of perception and by the spectral characters of daylight as it emerges after diffusion within the petals, these characters being themselves dependent on the quantity of floral pigment contained in the petals and its absorptive properties.

In the preceding chapter, a scheme for the classification of floral colours was suggested, based on the subdivision of the visible spectrum into four parts, consisting respectively of the blue sector, the green sector, the yellow sector and the red sector. Of these four, the yellow sector covers the narrowest range of wavelengths but nevertheless transcends all the others in respect of its influence on the perceived colour. Placing the four sectors in the order stated and indicating by the symbol 1 the absence of absorption and by the symbol 0, a complete absorption of the sector concerned, we obtain sixteen categories of colour which are indicated by the appropriate symbols. The eight categories which here concern us are (1111), (0111), (0011), (0001), (0000), (1001), (1011) and (1101). These represent colours which may be termed respectively as white, yellow, orange, red, black, pink, rose and purple. These assignments are based on spectroscopic observations of a great many flowers exhibiting various colours. If the absorption of light is not actually complete for any particular sector, the colour sensation which results is weaker, but is not altogether different. Thus the categorisation of colour may be regarded as having an extensive range of validity. Its usefulness depends on the fact that it enables us from the perceived colour to infer the part or parts of the spectrum where the absorption by the floral pigment is effective, and then proceed to verify this by direct observation.

Spectroscopic behaviour of roses: To ascertain the region or regions of the spectrum on which the floral pigments exercise their specific absorption, all that is necessary is to hold the flower in sunlight, or alternatively in diffuse daylight of sufficient intensity and view it through a direct-vision spectroscope. Comparison with the spectrum of a white diffusing screen observed under similar conditions immediately reveals the nature and extent of the alterations in the spectrum of the flower resulting from the presence in its petals of the floral pigment or pigments. This simple technique reveals that the absorption in roses which exhibit the various shades of cream or yellow appears in the blue sector of the spectrum, in other words in the wavelength range between 400 and 500 m μ , while other parts of the spectrum are entirely unaffected. The absorption is partial when the colour is a cream or a pale yellow. But it is more strongly manifested by the more vividly

coloured roses and is complete in the cases of roses which exhibit a deep yellow colour.

The spectroscope reveals that the soft pink colour of the Indian rose referred to at the commencement of this chapter has an entirely different origin. On a comparison of the light diffused by it and by a white screen, it is seen that the red sector of the spectrum appears with undiminished intensity and that the blue sector also appears with practically undiminished brightness. On the other hand, the green sector ranging from 500 to 560 $m\mu$ is much weakened, and the yellow sector between 560 and 600 $m\mu$ is just perceptibly dimmed. A fuller idea of the spectroscopic behaviour of the floral pigment contained in the petals of this rose may be obtained by examining the light which penetrates through its individual petals when they are held up against the bright sky and the slit of the instrument is held immediately behind the petal. Making this observation first with a single petal held by itself and then with two petals, then with three petals and finally with four petals held together, we find that while the red sector comes through freely in all cases, the green sector is progressively weakened and is almost completely extinguished when three petals are held together. The blue sector which is conspicuously visible with one petal is weakened in its passage through two petals, and is only seen with difficulty through three petals. A progressive weakening of the yellow sector is also evident as the number of petals is increased. With four petals, we have a complete extinction of all the sectors except the red which remains conspicuously visible.

It may be inferred from what has been stated above that the pink colour exhibited by many roses has its origin primarily in the absorption of light appearing in the green sector of the spectrum; the more complete this absorption is, the deeper would be the pink. Observations with roses exhibiting different shades of pink indeed show a progressive change in the spectral characters of the light diffused by the petals analogous to those described above resulting from the passage of light through a number of petals held together.

Red and crimson roses: Examination of the light diffused by the petals of roses which exhibit a red colour as also of those which appear of a crimson hue, reveals some remarkable features. The green sector of the spectrum is much weakened. But, in addition, we observe a dark band covering the wavelength range from 560 to 600 $m\mu$, in other words a complete extinction of the yellow sector of the spectrum. The blue sector of the spectrum is much weakened but is not totally extinguished. The wavelength region between 480 and 500 $m\mu$ also appears distinctly darker than the parts of the spectrum on either side of it. In the spectrum of the light transmitted through a petal of a red or a crimson rose, the extinction of the green sector between 500 and 560 $m\mu$ is complete, while the red sector is seen in full strength. The blue and yellow sectors are much weakened but not totally extinguished.

Scarlet roses: The roses exhibiting a scarlet hue form a distinct class by themselves. The difference in colour between a scarlet rose and a red rose is sufficiently striking to be unmistakable. It also reveals itself in the character of the spectrum diffused by the petals. The scarlet colour arises from a strong absorption in the wavelength range between 480 and 560 m μ . Light of greater wavelengths however comes through freely. The blue sector is weakened but can nevertheless be observed. As seen by transmission through the petals, the same features are noticed but are then more accentuated. The difference between scarlet and red roses thus lies in the greater transparency of the former to the yellow sector of the spectrum.

Orange roses: The transparency to the yellow of the spectrum exhibited by the scarlet roses is shown even more conspicuously by the roses of an orange hue. Here again, the perceived colour is a consequence of the absorption in the green sector between 500 and 550 m μ which is complete, while all greater wavelengths appear with undiminished strength. The blue sector is weakened but can nevertheless be observed in the wavelength range between 420 and 470 m μ . The blue sector is still weaker in the transmitted light, while the rest of the spectrum shows features similar to those observed by reflected light. The orange roses can thus be placed in the category (0011), but this description ignores the presence of the blue sector though much weakened in the spectrum. We have here a clear case of the masking of a weaker by a stronger sensation, the effect of the yellow and red sector acting in concert overpowering that of the weakened blue sector.

Extraction of the floral pigments: It is quite easy to remove the pigments from rose petals and thereby enable their absorption spectral to be independently studied. All that is necessary is to place the petals in a glass beaker and pour sufficient acetone to cover them completely. In a very few minutes, the pigments are dissolved out by the acetone, leaving the petals free from colour. The extract is quickly filtered and poured into the observation tube. It is useful to have four such tubes of different lengths, viz., 3, 5, 8 and 10 cm, each provided with flat ends. The quantity of the petals used can be varied suitably according to the depth of colour of the rose. For a deeply coloured extract, the tubes of smaller length are more useful. Vice versa, for weakly coloured extracts, the longer tubes are more convenient. Using this technique, a proper comparison between the pigments of roses exhibiting different depths of colour becomes possible. Two matters of detail may be mentioned here which are of some importance. The source of light used for the observations should be a tungsten filament lamp run at a high temperature to give white light of sufficient intensity. The observations should also be made with the acetone extract immediately after its preparation.

The absorption spectra of the floral pigments: It will suffice here briefly to record the results of the studies of the colour of roses as observed with the acetone

extracts. With yellow roses, we obtain solutions having a golden-yellow hue. Examination of the light transmitted through the observation tube containing the solution shows a complete absorption of the blue sector of the spectrum. Such absorption also extends a little beyond $500\text{ m}\mu$, exhibiting an ill-defined edge in the wavelength range between 490 and $520\text{ m}\mu$. The absorption spectra of the pigments contained in yellow roses thus resemble those of the carotenoids.

The colour of the extracts made with other roses depends a good deal on the quantity of the material used for the extraction and the volume of acetone added. Speaking generally, however, it may be said that the colour of the extract resembles the colour of the roses from which it is derived. The studies establish clearly that the pigments appearing in pink roses of various shades, in the red roses and in the crimson roses, are of an identical nature, the quantities of pigment present, however, being very different. In all such cases, with the appropriate concentrations, we observe a powerful absorption in the green sector, and in addition a fairly well-defined dark band in the wavelength range between 530 and $555\text{ m}\mu$. There is also a general absorption in the yellow sector extending from 555 to $600\text{ m}\mu$ and in addition a well-defined absorption band between 580 and $600\text{ m}\mu$. A general but rather weak absorption is also noticeable in the blue sector. It is most marked between 490 and $510\text{ m}\mu$.

The acetone extracts from the scarlet and from the orange roses differ from those of the other roses principally in respect of the absorption of the yellow sector of the spectrum. Such absorption is present in the extracts from scarlet roses, though it is not quite as strong as in the case of the pink, red, or crimson roses. On the other hand, the acetone extracts from the orange roses do not exhibit such absorption.

The new physiology of vision—Chapter XXIV. Floral pigments and the perception of colour

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Studies on floral colour are of great assistance in giving both breadth and depth to our understanding of the visual sensations excited by polychromatic radiation. We may recall here a few striking examples which have already found mention in earlier chapters. The tree known as *Lagerstroemia flos reginae* has two varieties, one of which exhibits great clusters of rose-coloured flowers, and the other produces similar clusters of flowers having a purple hue, flowers closely resembling each other in all other respects. Spectroscopic examination reveals that the rose-red flowers exhibit a nearly complete extinction of the green sector and thus belong to the colour category (1011), and that, on the other hand, the purple flowers exhibit an extinction of the yellow sector and hence belong to the category (1101). Similar and very striking differences appear in the spectra of the light transmitted through a bract of a rose-red variety of *Bougainvillea* and through a bract of a purple variety.

In numerous cases, the efforts of horticulturists to introduce improved varieties of flowers which enjoy popular favour have resulted in producing forms which exhibit more attractive colours as also new colours. Spectroscopic examination enables us to determine the spectral character of the light diffused by the flower petals of the different varieties and hence to connect their differences in this respect with the differences in their perceived colours. In the preceding chapter dealing with the colours of roses, we have already had an illustration of the usefulness of such studies, especially when they are supplemented by an examination of the absorption spectra of the floral pigments extracted from the petals with the aid of acetone as a solvent. The investigation revealed that great differences in the perceived colours can arise as a consequence of the same floral pigment being present but in very different quantities in the petals of the roses. On the other hand, it also emerged that differences in colour appear in various cases which are ascribable to actual differences in the nature of the floral pigments. The results obtained with the roses suggested that the matter would be well worth pursuing in other cases of interest. We shall accordingly devote the chapter to setting out some further significant results which have been obtained in this field.

Pelargoniums: These flowers (often referred to as geraniums) are highly esteemed by reason of their very attractive and continuous display of colour. The blooms appear in clusters, and these are massed against a green background of leaves of peculiar shape. One particularly brilliant and colourful pelargonium exhibits a scarlet hue, but there are also other varieties a comparative study of the colours of which is evidently called for. The spectroscope reveals that the scarlet-hued flowers show by reflected light the spectral range extending from $570\text{ m}\mu$ towards longer wavelengths, thus including both the red sector and a considerable part of the yellow sector. But the rest of the spectrum is missing, and in particular, the blue sector is not to be discerned. The brilliancy and high degree of saturation of the colour of the flowers are thereby made intelligible.

Examining other varieties of pelargonium, one meets with colours which are akin to scarlet but are less brilliant and less saturated in hue, e.g., orange, a pale orange and an orange-pink. The spectroscope reveals that they exhibit in addition to the part of the spectrum shown by the scarlet flowers, also part of the blue sector, while a gap appears between 480 and $550\text{ m}\mu$ which is evidently the region of the spectrum most strongly absorbed by the flowers. The varieties which exhibit the blue sector more strongly and the gap in the spectrum less conspicuously are also those in which the colour of the flower is less brilliant and less saturated in hue. This indicates that the same floral pigment appears in these varieties as in the scarlet pelargoniums but in smaller quantities. This inference is confirmed by extracting the pigment from the scarlet flowers using acetone as a solvent. On diluting the extract by addition of acetone, we observe similar progressive changes in the colour and spectral character of the light transmitted by the solution.

There are also other pelargoniums which evidently form a class by themselves, viz., those exhibiting a red colour, rose-pink and pale pink hues. In all these cases, the red sector of the spectrum makes its appearance but the yellow and the green sectors are weakened, while, on the other hand, the blue sector of the spectrum continues to be visible. The extinction of the yellow and the green sectors is complete in the case of the red flowers, but less so in the case of the rose-pink or pale pink varieties. The blue sector also gains intensity in the latter cases. One may infer from these facts that the floral pigment present in pelargoniums is different in the scarlet and in the red varieties. In the latter, the pigment has a strong absorption in the yellow sector of the spectrum, while in the former such absorption is absent. This inference is confirmed by extracting the pigments respectively from the two varieties of flowers using acetone as a solvent and examining the spectrum of the light transmitted through a column of the extract under comparable conditions.

Hibiscus rosa sinensis: Reference has been made in an earlier chapter to the large brilliantly coloured flowers of this plant. Seen either by reflected or by transmitted light, its petals exclude all parts of the spectrum of wavelength less

than $600\text{ m}\mu$, thus accounting for their red colour. The characters of the floral pigment responsible for this spectral behaviour are better understood when it is extracted with the aid of acetone, leaving the petals colourless. The extract exhibits a deep red colour and an intense absorption covering all wavelengths less than $600\text{ m}\mu$. Using short absorption paths or else by diluting the extract with acetone, thereby allowing light of smaller wavelengths to come through, a strong absorption band between 580 and $590\text{ m}\mu$ reveals itself, as also another strong band between 530 and $550\text{ m}\mu$. There is also a weak absorption band at about $500\text{ m}\mu$. The blue sector of the spectrum can be seen coming through, though only weakly.

A rose-pink hibiscus (a hybrid of the *rosa-sinensis* type) has also been examined. As seen by reflected or by transmitted light, its petals showed a powerful absorption of the green sector, the rest of the spectrum remaining practically unaffected. The flower thus belongs to the colour category (1011). The acetone extract of the pigments of the flower examined in a 2 cm absorption tube showed a rose-pink colour. The blue sector of the spectrum could also be seen coming through very clearly. Absorption bands could also be seen in the green and the yellow sectors in the same positions as with the extracts from the red hibiscus. There is thus good reason for assuming that the pigments in the two cases are identical. Longer columns showed the change in colour from a rose-red to a deep red to be expected in the circumstances and also a more powerful absorption of all wavelengths less than $600\text{ m}\mu$.

Hibiscus syriacus: The plant thus named is a native not of Syria but of India and is common in Indian gardens. It differs from *Hibiscus rosa sinensis* in the shape of its leaves and also in the manner of its flowering, the blooms appearing along the stem of the plant in the axils of leaves. The flower when it fades and closes up exhibits a blue exterior. But when the flower is open, the petals exhibit a purple hue. Spectroscopic examination reveals that this has its origin in the appearance of an absorption in the region of the yellow sector from 560 to $590\text{ m}\mu$, the rest of the spectrum presenting its normal appearance. The flowers of *Hibiscus syriacus* (*Indica*) thus belong to the colour category (1101). The floral pigment can be extracted using acetone as solvent. The extract has a beautiful purple colour and transmits both the blue and the red sectors freely. With short columns, a strong absorption band appears in the yellow sector of the spectrum covering the spectral region from 560 to $590\text{ m}\mu$. With longer columns, this region is completely extinguished, and a weak band in the green between 510 and $530\text{ m}\mu$ also makes its appearance. A very weak band is also seen in the red sector between 610 and $630\text{ m}\mu$.

Bignonia magnifica: This is a climbing plant which grows vigorously and is very showy, as it bears flowers in great profusion in large panicles. The colour of the fresh flowers is a rich purple. Examination of the spectrum of either the reflected

or the transmitted light shows that the pigment present in the petals exercises an absorbing power in the spectral range between 500 and 600 $m\mu$, this being much more pronounced between 560 and 590 $m\mu$, thereby effecting a nearly complete extinction of the yellow sector of the spectrum. On the other hand, the red sector is unaffected, while the blue is only slightly weakened. If the flowers are kept immersed in water for 24 h, the extraction of the pigment by use of acetone becomes readily possible. The acetone extract (if not too highly concentrated) exhibits a purple colour by transmitted light. Wavelengths greater than 600 $m\mu$ are freely transmitted and the blue sector also comes through, though sensibly weakened. Two dark bands are seen in the spectrum, one between 530 and 550 $m\mu$, and another between 580 and 590 $m\mu$, while the region from 550 and 590 $m\mu$ has its intensity reduced to a small fraction of its normal value.

The purple orchids: Of particular interest is the spectroscopic behaviour of orchids which exhibit a purple colour. The author has had an opportunity of examining several such orchids and found that they behave similarly. It is therefore sufficient here to consider the particular orchid known botanically as *Spathoglottis plicata*. This is a native of India and it is very hardy and can be grown on the ground or in pots like any other ordinary plant. The flowers are produced on spikes two or three feet long and the plant can easily be recognised by its palm-like leaves and the long spikes which hang out and bear flowers along their length and at their ends. The remarkable feature is that the spectrum of the light either reflected by or transmitted through the petals of the orchid exhibits a clearly defined set of absorption bands well separated from each other. The first band which is sharp and quite dark covers the spectral range from 575 to 600 $m\mu$ and thus in effect extinguishes the yellow in the incident light. The second band is not quite so dark nor is it quite so well defined. It appears in the spectral range between 530 and 555 $m\mu$. A third and much weaker absorption is noticed in the spectral range between 490 and 510 $m\mu$. The rest of the spectrum including both the red and the blue sectors remains unaffected.

The floral pigment can easily be extracted from the petals of the purple orchids with the aid of acetone. The extract has a purple colour by transmitted light and exhibits the three absorption bands in the same positions. But there is a remarkable change in their relative intensities. The second band appearing in the green is now more conspicuous than the first band in the yellow. The third band is also quite conspicuous. Finally, the blue sector shows a distinct weakening. It will be noted that the positions of the absorption bands both as seen directly with the petals and also in the acetone extracts are the same as those observed in the transmission of light by acetone extracts of red roses as set out in the preceding chapter. It is thus clear that we are here concerned with a definite chemical entity which plays a highly important role in the production of floral colours. What is specially remarkable is that when it appears in the petals of orchids, its spectroscopic behaviour manifests itself in such a clear and unmodified fashion.

Petrea volubilis: This is the botanical name of a climbing plant which is a great favourite in Indian gardens by reason of the beautiful sprays of purplish-blue star-like flowers which it bears in profusion and which give the plant the popular name of the Purple Wreath. Racemes of flowers which are from 15–20 cm in length crowd the plant, covering it up in a mass of colour. The most prominent feature of these sprays are the calices which remain after the true flowers have fallen off. The latter are quite small and their five petals have a much deeper colour. They can be seen resting on two or three of the end calices, one of the five having a white splash in the middle.

Spectroscopic examination shows that the colour of the sprays which is very striking as seen from a distance owes its origin to a weak absorption which manifests itself in the wavelength range between 570 and 600 $m\mu$ and results in a sensible reduction of the intensity of the yellow sector of the spectrum, while the rest of the spectrum is not visibly unaffected. The tiny flowers of a deeper colour show the same feature but in a more accentuated fashion, and give also an indication of an absorption band in the red at about 620 $m\mu$.

The floral pigment which gives rise to the observed colour can be readily extracted from the flowers using acetone as a solvent and its absorption spectrum can be studied by observations on the light transmitted through a column of the extract of appropriate length. The extract can be prepared using either only the calices or only the true flowers. The results are of the same nature in both cases. The colour of the transmitted light is purple. Two bands are visible in the green sector of the spectrum, one between 520 and 535 $m\mu$, and the other between 560 and 580 $m\mu$, the latter being much the stronger of the two. A third absorption band is also observed in the red sector between 615 and 630 $m\mu$.

Iris germonica: Iris form a very interesting class of plants which are remarkable for their curiously constructed flowers of attractive and gorgeous colours. *I. germonica* has creeping root-stocks, sword-like leaves and bears flowers on erect stocks. The particular variety studied has flowers which exhibit petals of a blue-violet colour. Spectroscopic examination of the light diffused by the petals shows a large diminution of the intensity of the yellow sector of the spectrum and also a strong absorption in the red sector. The floral pigment can be readily extracted with acetone and the solution exhibits a beautiful purple colour. Spectroscopic examination of the light transmitted through a 2 cm tube shows three absorption bands one in the green between 510 and 525 $m\mu$, another in the yellow between 550 and 580 $m\mu$ and a third in the orange red between 610 and 620 $m\mu$.

The new physiology of vision—Chapter XXV. The colours of natural and synthetic gemstones

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Glasses exhibiting colour are made by the addition of the oxides of various metals to the materials used in their manufacture. Amongst the additives used for this purpose in different cases may be listed the oxides of copper, cobalt, iron, nickel, chromium, manganese, titanium and uranium. Black, blue, green, amber, yellow, orange, red, purple and violet are amongst the colours that have been produced. We begin the present article with a reference to coloured glasses for the reason that they afford excellent illustrations of the role played by the characteristics of human vision in the production and perception of colour.

A familiar example of the use of coloured glass is for signal lights, viz., red, yellow and green. It is essential for such use that the colours perceived should be highly pronounced and distinctive, and that the glass should transmit light of sufficient brightness for it to be readily perceived. Examination of the signal glasses used on railways shows how these requirements are met. It is found that the red signal-glass cuts off completely the blue, green and yellow sectors of the spectrum and transmits only wavelengths greater than $600\text{ m}\mu$. The “green” signal-glass actually appears bluish-green and exhibits a free transmission of wavelength between 450 and $560\text{ m}\mu$, in other words, part of the blue sector and the whole of the green but cuts out completely the yellow and red sectors of the spectrum. The yellow signal glass shows a nearly complete extinction of the blue sector and transmits the rest of the spectrum without any noticeable absorption.

Blue glasses are of particular interest. Four specimens were examined which exhibited different depths of colour. All the specimens showed an absorption of the yellow over the wavelength range between 570 to $600\text{ m}\mu$. This absorption was evident even in the case of the most lightly coloured specimen and progressed to a complete extinction in the case of the most deeply coloured glass. All the four specimens also exhibited an absorption band in the red located at $650\text{ m}\mu$ and in addition a general absorption in the red region of the spectrum. A weak absorption was also noticeable in the green between 510 and $540\text{ m}\mu$ and this was progressively stronger with increasing depth of the colour exhibited by the glass. In all cases, there was a free transmission in the green between 540 and $570\text{ m}\mu$.

This appeared in the case of the deep blue glass as a bright band in the spectrum with dark bands on either side of it.

In the collection of specimens of glass presented many years ago to the author by the American Optical Company, there is a piece of spectacle glass which exhibits a brilliant blue-green colour by transmitted light. The spectroscope reveals that this colour results from a free transmission of the blue and the green sectors of the spectrum and a complete cut-off of the yellow and the red sectors. This specimen as well as the other cases mentioned above illustrate the extremely important role played by the yellow sector of the spectrum in the perception of colour. Only when the yellow sector has been completely eliminated by absorption can red, green or blue manifest themselves to perception as highly chromatic sensations.

Blue glasses also illustrate the general principle that in the perception of colour, strong sensations may mask sensations which are much weaker and prevent their being perceived. Thus, when the yellow has been eliminated, the blue sensation becomes dominant and prevents the green and the red from being perceived even though they are present in the spectrum. In general, however, composite sensations are experienced, the nature of which is determined by the particular circumstances of the case.

Colours of synthetic corundum: As is well-known, cylindrical boules of crystallised alumina can be prepared by the Verneuil process which are perfectly colourless and transparent if pure alumina is employed, but can also be made exhibiting varied colours by the use of appropriate additives. A collection of such boules prepared by an Indian manufacturer was available for study. The collection included fourteen colourless boules besides an equal number of specimens showing various colours, viz., three blues, one yellow, four greens, two purples and four reds. We shall proceed to describe the results of a study of these specimens.

The three *blues* showed essentially the same spectral pattern of absorption but developed to different extents. All the three specimens showed an extinction of the yellow of the spectrum in the wavelength range 570 to 600 m μ . Two other bands of absorption were also observed, one in the green from 540 to 550 m μ and another in the red from 630 to 660 m μ . The parts of the spectrum in the green, orange and red which were actually transmitted had apparently no effect on the colour of the light perceived which was a clear blue for all the specimens though the luminosity varied from specimen to specimen.

The *yellow* boule showed a rather pale colour which was the result of a diminished transmission of the blue region of the spectrum. The four *green* boules also did not exhibit that colour in any striking fashion. Both the red and the blue sectors showed a diminution of intensity in the transmitted light, and the yellow was also weakened. But in the net result, the green sector did not show any

particular degree of prominence in the spectrum. The poverty of the resulting colour was therefore not surprising.

Of the two *purple* boules, one was of a much deeper colour than the other. But even the faintly coloured specimen showed a readily observable diminution in the intensity of the yellow sector relatively to the rest of the spectrum. The more strongly coloured specimen showed a nearly complete extinction of the yellow of the spectrum over the wavelength range from 560 to 600 $m\mu$, while the red, green, and blue sectors maintained their normal relative intensities.

The *red* boules owed their colour to an absorption of light manifesting itself in the wavelength range between 500 and 600 $m\mu$. Two of the boules which were optically clear and perfect showed the phenomenon of dichroism in a very striking fashion. The colour of the boule as seen by transmitted light showed a large change when it was viewed transversely and rotated about its cylindrical axis. In one position, the colour was a rose-red, the spectrum exhibiting a relatively weak absorption in the green with its maximum around 550 $m\mu$. In the other position, the colour was a deep purplish-red and the absorption was practically complete over the wavelength range from 500 to 600 $m\mu$, thus covering both the green and yellow regions in the spectrum.

Colours of natural corundum: As is well-known, the gravel-beds below the soil in the vicinity of Ratnapura in Ceylon have for many years been the source of gemstones of various sorts. Some years ago, while on a visit to Ceylon, the author was the recipient of a generous presentation of some hundreds of specimens of the materials found at this site. They were sorted out and preserved and have been made use of for the observations presently to be described. Many of the specimens were colourless and some of them were so heavily coloured as to be nearly opaque. Excluding these, the rest of the material could be classified in the following colour-groups: blue, purple, red, green and yellow. Under an ultra-violet lamp, these groups behaved quite differently. The blue and green specimens were non-luminescent. The purple and the red stones showed a red glow of varying degrees of brightness, while the yellow specimens exhibited an orange luminescence.

Spectroscopic examination of the transmitted light showed that the blue stones owed their colour to a more or less complete extinction of the yellow sector of the spectrum and a cut-off of wavelengths greater than 650 $m\mu$ at the red end of the spectrum. The spectroscope also revealed that the characteristic purple colour exhibited by numerous specimens in the collection had its origin in the powerful absorption exhibited by these specimens in the wavelength range between 560 and 600 $m\mu$, in other words, of the yellow part of the spectrum, while the blue, green and red sectors remained conspicuously visible.

The red stones in the collection are rather small and of irregular shape, and also not optically clear. The difficulties arising from these defects in the study of their spectroscopic behaviour was overcome by setting each specimen in an aperture

made in an opaque screen. Holding this close to a brilliant source of white light, enough light diffuses through the specimen to enable its spectral character to be observed. The spectrum observed in this fashion differs from specimen to specimen, and *pari passu* there is a variation in the colour of the emerging light and of its brightness. Certain general features were however noticeable. In all cases, the red sector of the spectrum emerged freely. Certain sharply defined absorption lines appeared in the region of greatest wavelengths, but despite such absorption, the red remained the brightest part of the spectrum. The spectral region between 500 and 600 m μ also exhibited absorption. But the strength and the spectral range of this absorption varied from specimen to specimen. As a consequence of the weakening of the green and yellow sector in the spectrum, the red becomes dominant and determines the observed colour. In this, it is aided by the absorption noticeable in the region of shortest wavelengths in the blue sector.

The “green” stones in the collection could be more accurately described as greenish-yellow. They owed their colour to a strong absorption of the light in the blue and blue-green parts of the spectrum and to a very noticeable weakening of the red sector. The “yellow” stones owed their colour to a partial absorption of the blue sector, the rest of the spectrum remaining unaffected.

The green colour of emerald: The variety of beryl known as emerald shares with ruby and sapphire the rank of ‘precious stone’ in the popular estimation and, as with the corundum gems, its rarity and costliness have served to stimulate man’s ingenuity in providing artificial substitutes. Just as the red of ruby and the blue of sapphire cannot be properly matched by any other natural mineral, so is the pure emerald green unequalled by any other transparent natural gemstone.

Beryl is a silicate of beryllium and aluminium and the colour of emerald is due to traces of chromium, which replaces to a small extent the aluminium ions in the crystal lattice of the hexagonal lattice of the hexagonal beryl crystal. It is a feature of this colouring agent which also causes the red in ruby and in spinel and the betwixt-and-between colour in alexandrite, that even when it produces a green colour, it transmits a proportion of deep red light.

The foregoing quotations from B W Anderson’s book on Gem Testing state very clearly the reasons why the emerald is held in such high esteem, viz., its beautiful green colour and the rarity of material of the requisite high quality, which together make it a much valued gemstone. It should be mentioned that beryl is itself a mineral of fairly common occurrence and that though it is colourless in the pure state, it frequently exhibits colour, this presumably arising from the presence of impurities. Iron is the impurity responsible for the familiar bottle-green colour of cheap glassware; oxides of iron if present in beryl as impurities would also give it a green colour. But it is not difficult to recognise the special variety of beryl in which the colour arises from the presence of chromium as an impurity. Spectroscopic examination reveals the presence in such cases of a group of sharply-defined absorption lines falling within the wavelength range

between 600 and 700 $m\mu$, and indicating the presence of chromium in the crystal lattice.

The author had at his disposal an extensive collection of beryl specimens including especially several which had a green colour. A few of these were large and clear enough to permit of the absorption spectrum being seen by merely holding up the specimen against the sky and examining the transmitted light through a pocket spectroscope. In most cases, however, the specimens were either too small or else were not optically clear enough to permit of their being thus dealt with. In such cases, the specimens were set within an aperture in an opaque screen and this was held close up to a brilliant source of white light. The light emerging through the material could then be conveniently examined. To make the present study more complete, the author used besides the beryls at his disposal also a real emerald of small size but of good quality and two specimens of the well-known synthetic product made by Mr Carroll F Chatham of San Francisco and marketed under the trade name of "Chatham Created Emerald".

The comparative study of these specimens made it evident that the beautiful green colour of emerald owes its origin to the absorption of the yellow sector, in other words of the wavelength range in the spectrum between 560 and 600 $m\mu$. The more complete this absorption is, the more striking is the green colour which results. The removal of the yellow sector and the simultaneous weakening of the blue and red sectors leaves the green as the dominant feature which determines the observed colour. It should be remarked that the blue and red sectors are not completely extinguished in any case. But they are so weak that they are masked by the stronger green and prevented from being perceived. The larger of the two Chatham emeralds examined by the author shows the absorption of the yellow sector in a particularly striking fashion. The red sector, though weakened, is also very clearly seen and exhibits the characteristic absorption lines due to the chromium impurity with extreme sharpness and clarity.

The new physiology of vision—Chapter XXVI. Structural colours

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The studies of the visual synthesis of colour described in several of the preceding chapters were made with various materials exhibiting highly pronounced colours by reason of their ability to absorb certain well-defined regions in the spectrum while freely transmitting the rest. The reason for choosing them as the subject of study was, besides the availability of the materials, the possibility by making use of them of arriving at definite conclusions regarding colour and its relation to the spectral constitution of light. There are, however, numerous other ways in which colours can arise and be perceived. It is clearly desirable that such cases should also receive consideration in our survey of the origins of colour and its visual perception.

The colours of interference: The colours of thin films are amongst the most familiar phenomena in physical optics and we naturally begin by considering their nature and origin. A very convenient way of producing them for the purpose of a detailed study is to put together two similar flat plates of glass, each about half a mm thick and two or three cm square in area. When pressed into contact after careful cleansing, they adhere in certain areas and are separated by an air-film in other areas. As seen by reflected light, the areas of adhesion appear quite black, while the other regions exhibit colour. It is often possible to get the plates adhering all along the outer edges, while the area within shows a sequence of interference colours appearing as a series of closed curves.

It is a significant fact of observation that the colour sequence in the fringes exhibited by air-films of progressively increasing thickness is the same irrespective of whether the fringes are straight or curved or irregular, irrespective of whether they are broad or narrow, and irrespective of whether they are equally or unequally or even randomly spaced. These facts become intelligible if it be recognised that the lines of colour follow the contours of luminosity in the field. The illumination at any point in the field of observation is determined by the thickness of the air-film at that point and its relation to the wavelength of the part of the spectrum which is visually the most effective. This is the yellow sector of the spectrum and its average wavelength may be taken as $580\text{ m}\mu$. Where the

luminosity of the field as determined by the thickness of the air-film in relation to this wavelength is a maximum, the field would exhibit a yellow colour, and the rest of the spectrum would have but little chromatic effect. *Per contra*, it is in those parts of the field where the intensity due to the yellow sector is zero or small, that the other colours in the spectrum can manifest themselves most clearly.

The regions of zero intensity for light of wavelengths greater than that of yellow light and for light of wavelengths less than that of yellow light would evidently adjoin the regions of zero illumination for yellow light, but would be located on opposite sides of the same. Hence, in the regions where the light of such greater wavelength has a low intensity, the light of the smaller wavelengths would be dominant and determine the observed colour. Vice versa in the regions where the light of the smaller wavelengths has a low intensity, the light of the greater wavelengths would dominate and determine the observed colour.

The foregoing considerations are fully supported by the actual facts of observation. In particular, it is evident on inspection that the bands of colour follow the contours of minimum luminosity in the field and that the colours are most vivid in the regions adjoining them on either side. On the other hand, along the contours of maximum luminosity, the colour exhibited is yellow, while green and red appear respectively on the two sides of the lines of minimum luminosity.

The classic illustration of the colours of interference is the phenomenon first described by Newton and known by his name which is exhibited by an air-film between two polished surfaces of glass having different curvatures. The interferences appear as circular rings surrounding the point where the two surfaces are in actual contact, this appearing as a black spot. If the rings are formed between two surfaces of which the curvatures are not nearly the same, the area over which the interferences are visible in white light would necessarily be limited and the successive rings would be close to each other. In such cases, it is found that though the rings can be seen quite clearly when the air-film is held at the usual distance of distinct vision from the eyes of the observer, no colours are visible, the pattern exhibiting only variations of brightness. Five or six rings can be counted, the contrast between the dark and bright rings falling off in the successive rings. To observe colours in such cases, it is necessary to examine the interference pattern closely through a magnifier. The colour-sequence as described earlier can then be recognised.

The explanation of the remarkable facts stated above is not far to seek. Newton's rings exhibit the fluctuations of luminosity which arise from interference as observed in white light and the appearance of colour is only an incidental circumstance. The eye perceives only the fluctuations of brightness and does not perceive any differences in colour unless the regions in which the spectral characters of the light differ are widely enough separated for the eye to recognise them as distinct areas in the field.

The colours of rotary dispersion: Very interesting cases in which structural

colours are observed present themselves when plane-polarised light traverses a crystal having a chiral structure. The best known example is that of quartz. The colours under reference are observed when a plate of this crystal cut perpendicular to its optic axis is set between two polaroids and a bright source of light is viewed through the combination. To observe the colours at their best, one should use a pair of polaroids which give a perfect extinction of light without perceptible colour when they are in the crossed position. The rotation of the plane of polarisation produced by the passage through the crystal is proportional to the thickness of the plate and depends on the wavelength of the light. Hence when a plate of any particular thickness is used, it is possible to extinguish any specified part of the spectrum by a suitable setting of the polaroids with respect to each other, while the rest of the spectrum is transmitted. As the position of the spectral band of extinction can be varied by rotating one of the polaroids, the spectral constitution of the emerging light is altered and its observed colour also changes. By using a set of quartz plates of different thicknesses, the relation between the perceived colour of light and its spectral constitution can be studied in this manner in a great many different cases.

In the present studies, seven plates of quartz of different thicknesses were used. Four of the plates had thicknesses which were fractions of a mm, while the three others had thicknesses of three, five and six mm respectively. These thicknesses and the optical rotations to which they give rise to for various wavelengths are shown in table 1. The figures were computed from Chandrasekhar's formula which is quite simple and represents the optical activity of quartz with great accuracy over the entire range of wavelengths.

Table 1. Rotation in degrees of arc for different wavelengths.

Plate thickness (mm)	400 mμ	450 mμ	500 mμ	550 mμ	600 mμ	650 mμ
0.46	23	18	14	12	10	9
0.68	34	27	21	17	14	12
0.84	42	33	26	21	18	15
0.96	48	38	30	24	20	17
3.00	150	117	93	75	63	54
5.00	250	195	155	125	105	90
6.00	300	234	186	150	126	108

When a plate of quartz is interposed between two crossed polaroids, there is a restoration of light which cannot be quenched by a rotation of one of the polaroids. It is however possible in the case of the quartz plates of the thicknesses listed in table 1 to find a setting in which the light emerging through the combination has the minimum brightness. In these circumstances, the emerging

light is found to exhibit a purple colour. A rotation of the polaroid away from this setting in one direction or the other results in a brightening of the field as well as a change of colour, this being different for the two directions. In one case, the field exhibits a blue colour and in the other case it becomes bright yellow. The magnitude of the rotation required for the change of colour from purple to blue or from purple to yellow increases with the thickness of the plate. Transitional colours appear in the intermediate stages.

Spectroscopic examination of the light of purple colour emerging along the optic axis at the setting for minimum transmission reveals a dark band of extinction covering the yellow sector, the green and blue sectors being clearly visible on the one side and the red sector on the other side of the spectrum. A rotation of the polaroid away from that setting results in a displacement of the extinction band in the spectrum; it moves from the yellow to the green or from the yellow to the red respectively for a rotation in the two directions. Such spectral displacement results in an increased brightness of the transmitted light and also a change in its colour.

The magnitudes of the rotation for different wavelengths listed in table 1 enable us to understand why the colour of the transmitted light is blue for some settings of the polaroids and yellow for other settings. The colour is determined by the luminosity of the blue and green sectors relatively to the yellow and red sectors in the spectrum of the transmitted light. The great difference in rotatory power at the two ends of the spectrum results in the short-wave end or the long-wave end becoming its dominant feature as determined by the setting of the polaroids. In the former case, the resultant sensation is blue, and in the latter it is yellow.

The difference in the optical rotation at the two ends of the visible spectrum is less than 180° for all the plates listed in table 1 except the thickest for which it is slightly in excess of that value. Hence, only one extinction band can appear in the spectrum of the transmitted light and this would shift from one end of the spectrum to the other as one polaroid is rotated, finally passing out of the spectrum altogether. When the latter is the case, the transmitted light could, if at all, exhibit colour only by reason of the altered distribution of intensity in the spectrum which results from the presence of the second polaroid. The effects thus arising are scarcely noticeable in the case of the four thinnest plates. They are, however, observable in the case of the plates which are three or five mm thick, and are quite conspicuous in the case of the six mm plate.

The colours of the sky and the sea: When white light traverses a transparent medium, its molecules scatter or diffuse the radiation and the light thus diffused when perceived by the observer is found to exhibit colour. The explanation of this effect usually given is that the scattering power of the medium depends on the wavelength of the radiation traversing it. The proportion of the scattered to the incident light varies inversely as the fourth power of the wavelength and is thus much greater for the short-wave regions in the spectrum than for the long-wave

part of it. This argument is clear enough from a physical standpoint; but it leaves the actual facts of the case, viz., the perception of a blue colour, without any real explanation. The inadequacy of the argument becomes evident when an observer views the blue sky through a pocket spectroscope and compares it with the spectrum of a white cloud floating in the sky. In both cases, the entire solar spectrum is visible and in both cases the green, yellow and red sectors are much more luminous than the blue sector. The blue sky is much less bright than a white cloud; hence the spectrum in the latter case is the more brilliant. Scrutiny reveals that this difference in brightness is more evident for the green, yellow and red sectors than for the blue sector. In other words, the blue sector gains relatively to the green, yellow and red sectors in the spectrum of the blue sky. Nevertheless, these sectors continue to be more luminous than the blue sector. Why then do we see the sky as blue while the cloud appears white?

The answer to the paradox stated above is furnished by the phenomena of the superposition and masking of colours which formed the subject of an earlier chapter. The sensation of white light is the result of the superposition of radiations appearing in the two parts of the spectrum of which the wavelengths lie respectively in the ranges from 400 to 500 $m\mu$ and from 500 to 700 $m\mu$. The superposition of radiations appearing only in the first range results in the chromatic sensation which we call blue. The superposition of the radiations appearing only in the second gives the chromatic sensation which we call yellow. When superposed in an appropriate ratio, these two sensations merge and give rise to an achromatic sensation. But if one is present in excess, either sensation can mask the other and prevent its being perceived. The presence of the sensation which is suppressed however makes itself felt as a dilution or weakening of the chromatic sensation which survives.

In diverse fields of experience, the foregoing ideas find confirmation. For example, many flowers contain the carotenoid pigments in their petals and exhibit a yellow colour. But the intensity of the colour varies from the palest cream to a rich golden hue as determined by the strength of absorption of the blue sector by the pigments. The familiar variations in the colour of the sky from the palest blue to the deepest azure are likewise explicable in terms of the spectral nature of the scattered light in various circumstances. As sunlight is progressively denuded of the components of shorter wavelength in its spectrum by traversing long paths in the atmosphere, a stage is reached when an observer would perceive its colour as yellow. Thus, the colours of the twilight sky can be explained on the same basis as the complementary phenomenon of the blue colour normally exhibited by the sky.

The molecular diffusion of light also plays a highly important role in producing the blue colour exhibited by the water in deep lakes and by oceanic waters when the turbidity which results in a lack of transparency is at a sufficiently low level. In such cases, it is noticed that the blue colour is much deeper than the colour of the sky. The reason for this difference is to be found in the absorption of sunlight

when it traverses long columns of water. This absorption is weak but selective, being confined to the long-wave region in the spectrum. This part of the spectrum would be weakened when the incident light traverses the medium and again after diffusion returns to outer space. As a result of these processes, there would be a large preponderance of the short-wave part of the spectrum in the diffused light emerging from the medium. The highly pronounced blue colour actually exhibited by such waters thus finds a natural explanation.

The new physiology of vision—Chapter XXVII. The colours of interference

SIR C V RAMAN

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The characteristic features and properties of human vision are exhibited in a very striking manner in the phenomena which will occupy our attention in the present chapter. The results here described have emerged from the author's own investigations. Strangely enough, though the experiments themselves have been familiar for three centuries, the phenomena which they exhibit have not till now been correctly observed and described and hence their real nature has been misunderstood.

A thin film of air enclosed between two flat or nearly flat plates of glass exhibits colours when it is viewed by the light reflected at the surfaces enclosing the film. The colours owe their origin to the interference of the beams of light reflected at the two surfaces which differ in their optical paths, such difference being itself determined by the thickness of the film. If, therefore, the thickness of the film varies over its area, the colours exhibited also vary and the pattern of colours follows the variations of thickness and serves to indicate their geometric configuration.

In the classical form of the experiment, the air-film is that enclosed between two surfaces, of which one is plane and the other spherical with a large radius of curvature. In these circumstances, the interferences take the form of rings which are concentric around the region of actual contact of the two surfaces where the film has zero thickness. This central region appears black in the pattern. Sir Isaac Newton devoted the second book of his classical treatise on optics to a description of these rings and hence they are usually known by his name. But neither Newton nor any of the numerous other observers who have described and discussed the effects observed in the experiment make any reference to the major feature of the phenomenon, viz., the manifestation of a series of maxima and minima of luminosity in the field covered by the pattern. These alternations of luminosity determine the characters of the interference pattern, and the alternations of colour observed are related to the alternations of luminosity in a manner which clearly indicates that the latter constitute the basic phenomenon and that the colour differences are only incidental consequences.

Newton's rings in white light: The area over which the interferences as seen by white light are recognisable depends on the radius of curvature of one surface, the other surface being assumed to be plane. In the apparatus employed, the surface which is spherical has a radius of curvature of 3.6 metres and the pattern as seen by reflected light extends over a circle of about 1 cm diameter. Holding the plates at the usual distance of distinct vision and viewing the pattern by reflected light without any optical aid, it exhibits a black centre around which can be seen a succession of bright and dark rings, but no colours are noticeable. The spacings of the rings progressively diminish. Six rings are readily distinguishable, while a few others beyond can be glimpsed, the difficulty in seeing and counting them being a consequence of the closeness of the outer rings as well as the diminishing contrast in brightness of the successive maxima and minima of illumination. While the first few bright rings are definitely more luminous than the outer field of illumination, this difference progressively diminishes as we proceed from ring to ring till finally the rings melt into a background of uniform illumination.

The observations described above make the real nature of Newton's rings evident, viz., that they represent fluctuations of visual brightness or luminosity in the field of view. To observe colours, it is necessary to examine the interference pattern more closely, using a magnifying lens of adequate power. The maxima and minima of brightness remain conspicuously visible but are then accompanied by manifestations of colour in a fashion closely related to the variations of luminosity in the field. What we actually observe with white light may appropriately be compared with the nature of the interferences which would be seen if monochromatic light in the yellow part of the spectrum were used to observe them. In the latter case, as is well-known, the entire field would be covered with a succession of maxima and minima of luminosity in great numbers, all the maxima being equally bright and all the minima being perfectly dark, the successive rings coming closer and closer together as we proceed outwards from the centre of the pattern. The differences between this case and the interferences as observed with white light may be stated as follows:

Firstly, with white light, the contrast between the maxima and the minima of luminosity diminishes progressively instead of remaining the same everywhere. The maxima themselves progressively diminish in brightness until they merge with the uniform field of brightness at a sufficient distance from the centre of the pattern. The character of the minima of illumination also alters progressively. The first minimum of illumination is highly pronounced, being almost perfectly dark. The second minimum of illumination is also conspicuous, indeed only slightly less so than the first. The third minimum of illumination is also quite pronounced, though much less so than the first or the second. The fourth minimum of illumination is clearly recognisable as such, while the fifth is only just noticeable.

Secondly, the manifestations of colour are very clearly related to the variations of luminosity in the field. What we may describe as a cycle of colours begins at

each minimum of luminosity and ends at the next minimum, where a fresh cycle commences and proceeds to the next and so on. At least six such cycles are clearly recognisable, beyond which a few more can be glimpsed. The characters of the cycle of colours show a rapid change as we proceed from the first to the second and then to the third, the subsequent cycles resembling each other pretty closely. In the first three cycles, the yellow colour of the circle of maximum luminosity is evident, but in the later cycles it is not to be seen, and we observe instead a rapid change of colour from green to red. In the earlier cycles, the progression of colour is more gradual. At each minimum, we begin with a blue or bluish-green and pass on to the yellow, and then through orange to red at the next minimum where the cycle terminates.

Measurement of the white light patterns: The comparisons made above between the nature of the interferences as observed with white light and those seen with a monochromatic yellow are significant. Since the minima of luminosity are conspicuously visible, their positions can be determined accurately and compared with those of the minima observed with monochromatic light of various wavelengths. For this purpose, the apparatus is placed on the stage of a Hilger micrometer of the kind commonly used for the measurement of spectra and a slip of glass held at an angle of 45° is attached to it. A horizontal beam of light from the source of light employed is reflected downwards by this slip and the interference pattern is then seen by the reflected light coming back through the slip. The spiderlines in the field of view can then be set on the minima of illumination one after another, tangentially to the circles seen in the field of view. The observations are first made with a small brilliant tungsten-filament source, and they are then repeated using monochromatic light of different wavelengths. The green 5461 \AA light of a mercury lamp, the yellow $5770\text{--}5790 \text{ \AA}$ light of a mercury lamp—in each case isolated by suitable colour filters—and the $5890\text{--}5896 \text{ \AA}$ orange-yellow of a sodium lamp are suitable for such comparisons. The measurements thus made show that the green line of mercury has a wavelength much less than the correct value, while the orange-yellow line of sodium has a wavelength definitely too large. On the other hand, the minima seen with the yellow lines of the mercury lamp agree excellently in their positions with all the minima of illumination observed with the tungsten lamp illumination. In other words, the minima of luminosity in the pattern observed with white light appear in the same positions as those produced with the yellow $579 \text{ m}\mu$ radiation of a mercury lamp.

The origin of the white light fringes: The foregoing observations establish that the wavelength $579 \text{ m}\mu$ has a special significance in relation to the visual perception of light and colour. The colour of light of that wavelength is a pure yellow; observations indicate that the yellow sector (in the spectrum of which the limits may be put as 560 and $600 \text{ m}\mu$ and) of which it is the centre which plays a dominant role in human vision. In those regions of the interference pattern where

this sector is weak or absent, the other colours of the spectrum can make an appearance. The region of wavelengths between 500 and 560 $m\mu$ may be designated as the "green" sector, and the region between 600 and 700 $m\mu$ as the "red" sector. The observed distribution of colour in the interference pattern becomes intelligible when it is remarked that the light in the red sector and light in the green sector would manifest themselves with adequate intensity on *opposite* sides of the region where the yellow sector has the minimum intensity. *Per contra*, in the regions where the yellow sector has the maximum intensity, the red and green sectors would have a negligible effect.

The picture of the nature of human vision which emerges from the present investigations is thus radically different from that envisaged in the so-called trichromatic hypothesis which assigns to the "green" and "red" sensations major roles in vision and regards "yellow" as a secondary or derived sensation, thus assigning to it a minor position in the perception of light and colour. Actually, we find that it is the yellow sector of the spectrum which plays the major role in vision, while the green and the red sectors play relatively minor roles, serving to supplement and extend the range of human vision respectively towards lesser and greater wavelengths beyond those covered by the yellow sector.

Other methods of observations: The fundamental importance of the results set forth above indicates the desirability of enabling the colours of interference to be exhibited in a more vivid fashion than is possible with the usual form of Newton's rings apparatus. Indeed, there is no necessity for any special apparatus for observing the interference colours of thin films of air. If two square plates of ordinary glass, each about half a mm thick and 5 cm in length and breadth are carefully cleaned and pressed into contact, they may be caused to adhere firmly all along their edges, leaving enclosed between them a thin film of air of varying thickness due to the plates not being absolutely plane. This film exhibits brilliant colours by reflected light and they may be made more impressive by blackening the rear surface of one of the plates. The interference patterns thus obtained usually appear as a set of closed curves. The edges where the plates are in contact appear perfectly black. The fringes running parallel to the edges exhibit maxima and minima of luminosity and cycles of colour, these being completely similar to the effects observed with Newton's rings except that they are on a larger scale and are manifest to the unaided vision.

Very striking effects can also be obtained with thicker plate-glass of the kind used for covering large windows. The methods of manufacture of such glasses ensure both smoothness of surface and a reasonably uniform thickness. Nevertheless, the residual deviations from planeness are sufficient to enable beautiful exhibits of interference colours on a large scale to be prepared from them. For this purpose, small square or oblong strips, a few cm in length and breadth, should be cut out using a diamond and the cut edges ground and bevelled to remove the resulting strains. If two such strips are carefully cleaned

and put together, beautiful interferences are obtained, the configuration of which may be altered by rotating the strips with respect to one another. Perfectly circular ring-patterns may be obtained, and also elliptic-ring patterns of various eccentricities but quite regular in shape. Putting the two plates together in a light frame of aluminium, they can be held together in an appropriate orientation so as to exhibit an interference pattern of the desired nature on a large scale (see figure 1 in plate I).

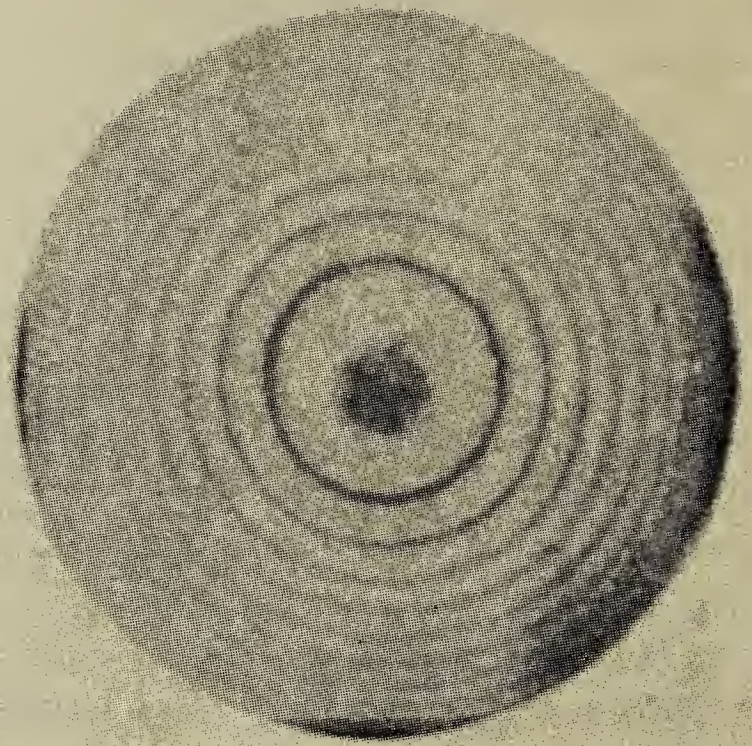
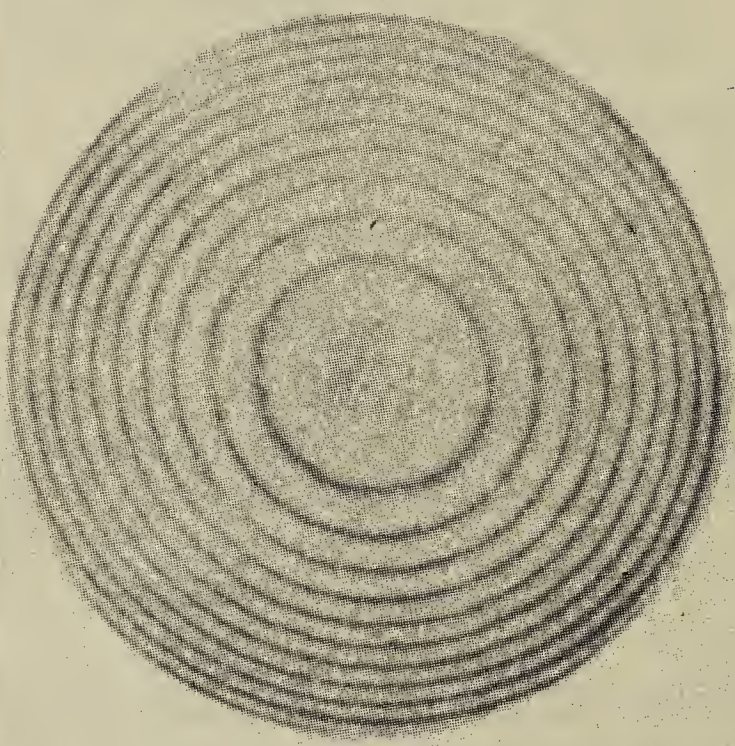
Another type of interference pattern may be obtained using two plates held together by metal clamps so as to be actually in contact all around their edges, so that the area enclosed by them shows interferences. In such cases, the interferences of zero order form a closed curve following the edges, while the interferences of higher orders are enclosed within the area. The number of closed curves seen is determined by the thickness of the air-film at the centre of the pattern (see figure 2 in plate I).

Another way of exhibiting interferences in a striking fashion is to use two disks of optical glass, one face of each plate being carefully worked as to make it as nearly plane as possible. If the two disks are held clamped together with these two faces adjacent, the pressure of the clamps being exerted near the end of one diameter, the wedge-shaped air-film then formed will exhibit a nearly straight series of fringes. The characteristic alternations of luminosity and the accompanying cycles of colour are very well shown by this arrangement (see figure 3 in plate I).

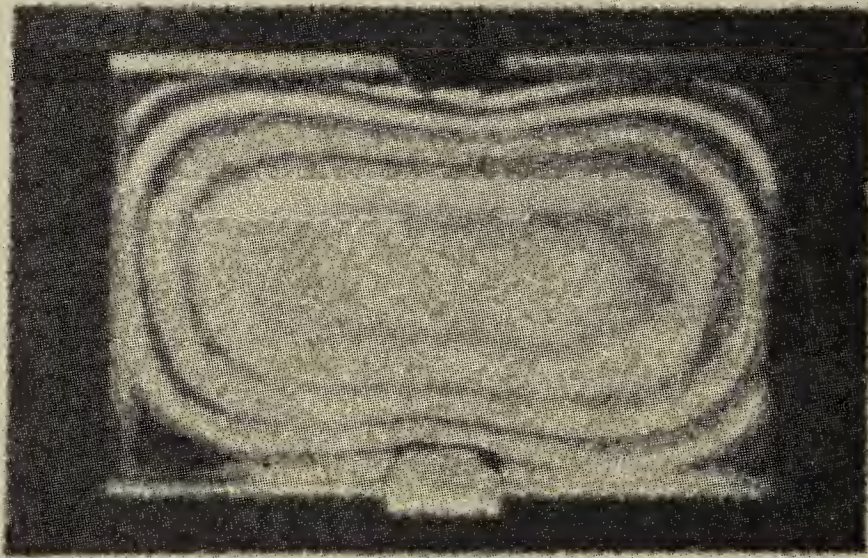
Explanation of Plate I

The pictures reproduced in Plate exhibit interference patterns obtained with the arrangements described above which were photographed using panchromatic plates.

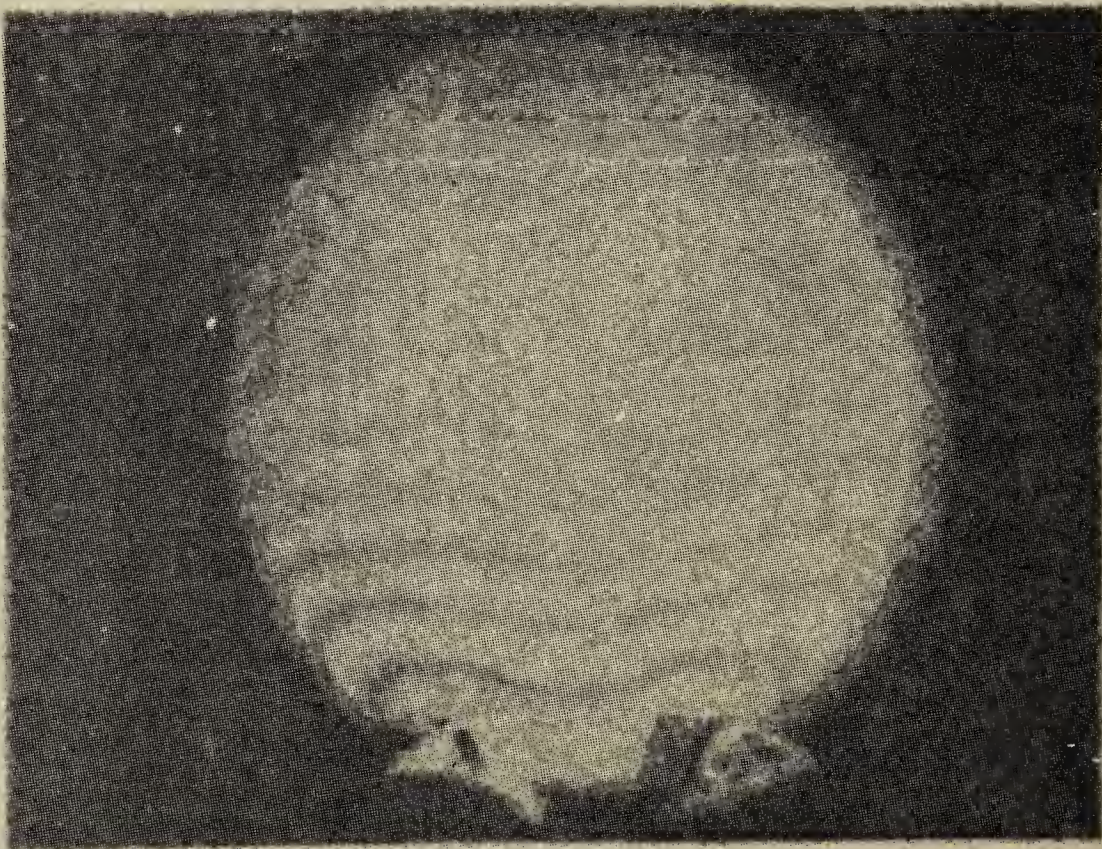
Figures 1–3. 1. Reproduces circular-rings similar to the familiar rings of Newton but on a much larger scale. The figure on the left was recorded with the light of a sodium lamp and that on the right with white light from a tungsten-filament lamp. 2. Reproduces the interferences due to an air-film with zero thickness all round its edges and a maximum thickness at the centre. The photograph was recorded with white light. 3. Shows the interferences of a wedge-shaped film recorded with white light.



(1)



(2)



(3)

Figure 1-3
Plate I (see p. 363 for captions)

The new physiology of vision—Chapter XXVIII. Observations with a neodymium filter

SIR C V RAMAN

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Glass disks coloured by neodymium oxide make useful filters with which it is possible to cut out the yellow light of a mercury lamp (5770–5790 Å), while allowing the green light of the lamp (5461 Å) to be freely transmitted. Some specimens of such glass being available, it appeared worthwhile to examine the effect of placing a filter made of it before the observer's eye when viewing luminous objects. The changes in their appearance noticed in various cases are of such a striking nature that it appears desirable to place the observations on record.

Three plates were available, each about 4 mm thick. Viewing the sky through a spectroscope with one such plate placed before the slit of the instrument, an intense and sharply defined absorption covering the wavelength range from 570 to 600 m μ is visible. In other words, the filter cuts out the yellow light from the spectrum. Feeble absorption bands are noticed in the green part of the spectrum between 500 and 530 m μ . There is also a noticeable weakening of the blue part of the spectrum between 460 and 480 m μ . These other absorptions become very prominent when all the three plates are put together. But when only one plate is employed, they could be considered to be of negligible importance in comparison with the complete exclusion of the yellow from the spectrum by the principal absorption band.

Luminosity and colour: The reduction in absolute luminosity produced by the introduction of the filter becomes strikingly evident when we view an intensely luminous field, as for example, a part of the sky not far away from the sun. This region which appears insupportably bright to the eye without the filter could be tolerated when the filter is put in. Clouds in the vicinity of the sun which dazzle the eye when looked at directly could be viewed and their texture critically examined through the filter. The large contribution to luminosity made by the part of the spectrum between 570 and 600 m μ is thus made evident.

The effect of removing the yellow from the spectrum is even more striking in respect of the colours of various objects viewed through the filter. These effects are indeed of a rather paradoxical nature. The blue sky seems bluer when viewed

through the filter. Green vegetation appears greener when seen through the filter than when viewed directly. Objects which normally exhibit red hues appear of a deeper and more saturated red colour. The explanation of these changes is not far to seek. A large contribution to the observed luminosity of the objects under view is made by the part of the spectrum between 570 and 600 m μ . When this is excluded by the filter, the luminosity of the object is reduced. At the same time the diluting effect of the yellow light on the colour of the perceived light is also abolished. The intrinsic colour of the object is thereby made more evident.

Many examples could be mentioned of the remarkable way in which the colours of familiar objects are altered by viewing them through the filter. Common sand and gravel laid on roads usually appear of a brownish-yellow colour by reason of their iron content. Viewed through the filter, they change to a brick-red hue. Fresh leaves which are of a greenish-yellow colour turn into a full green and appear like mature leaves, while mature green leaves turn into a darker green. Flowers are a particularly interesting study. Pelargoniums, for example, exhibit striking changes. Those which are of a pale rose-red hue appear quite red. Orange pelargoniums turn to a scarlet and scarlet pelargoniums to a bright red. Examples of such changes can be multiplied indefinitely. Perhaps the most startling effects are those exhibited by human complexions which when viewed through the filter appear suffused with blood. Striking changes also appear in the colours of the sky at the time of sunset, yellow hues turning to an orange red.

Colours of interference: Very interesting effects are observed when thin films exhibiting patterns of interference colour due to variable thickness are viewed through a neodymium filter. These effects are of different kinds, being respectively those noticed in areas where colours are ordinarily observable, those arising in the areas immediately surrounding them where little or no colour is ordinarily visible, and finally, those noticeable in more remote regions where the path differences are larger.

The first class of effects may be observed with Newton's rings or other arrangement exhibiting the colours of thin films of air. There is a notable reduction in the luminosity of the entire pattern and this is accompanied by striking changes in the distribution of luminosity as well as in the colours which are observed. The variations in luminosity as we proceed outwards from the centre of the pattern are less striking, though the first dark ring remains as a conspicuous feature. The spectral yellow along the circles of maximum luminosity disappears, while the colours seen in the adjoining regions gain in vividness. The cycles of the colour are replaced by green and red bands of strongly contrasted colour which are sharply demarcated from each other. Beyond the fifth ring of colour, numerous additional dark and bright rings spring into view. Some ten or twelve of these rings can be counted, five or six being perfectly achromatic, while those beyond which are less conspicuous appear edged with colour.

A convenient arrangement for observing the effects described above is to use two ordinary plates of glass each 10 cm^2 in area and about half a mm thick. After being carefully cleaned, the plates may be placed in contact so that only a thin film of air separates their surfaces. With a little gentle pressure, this air-film can be squeezed out from some areas which then exhibit interference colours. Viewing such an air-film through the filter, the various phenomena referred to above can be readily observed, and in addition, the entire area between the plates will be found to be covered with interference bands in areas where they would not be seen unless monochromatic light sources are employed.

We now proceed to comment on the explanation of the effects described above. It is well-known that by using a colour filter which cuts out most of the spectrum except a limited region, the number of interferences which can be seen and counted can be greatly increased. A red filter which cuts out all wavelengths less than $600\text{ m}\mu$ may be cited as an example. An orange filter which cuts out all wavelengths less than $550\text{ m}\mu$ produces similar effects but is not so satisfactory. The distinctive feature of the case with which we are now concerned is that the filter removes the limited region between 570 and $600\text{ m}\mu$ but allows the rest of the spectrum to pass through. That it also results in an increase of the visible number of orders of interference is significant but is not altogether surprising. The effectiveness of the filter in this case is due to the fact that the spectral regions adjoining the absorption band are both quite luminous, viz., the green sector and the red sector respectively. Hence, they can both give rise to readily observable interference patterns. The superposition of these patterns is evidently responsible for the effects observed in the various regions and the differences between them.

The new physiology of vision—Chapter XXIX. The reproduction of colour

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We live in a colourful world and we are educated by our environment to love and admire colour. The blue sky, the red glows of sunrise and sunset, the green colour of vegetation and the varied hues of flowers are always with us as a reminder of our ability to perceive colour and to distinguish even subtle differences in colour. Inevitably, therefore, man has sought to emulate Nature and to surround himself with various products of his own handiwork which display colours rivalling those of Nature. We need only mention a few examples. The dyeing of textiles and the production of ceramic wares are fields in which human ingenuity has sought to produce works of art which, while they derive their inspiration from the products of Nature, differ from many of them in exhibiting the quality of permanency.

A further consequence of the love of colour is the desire to record the fleeting scenes of colour with which Nature provides us in a more enduring form. The art of painting in colour had its origin in this desire, but has developed into one of the highest forms of expression of the human spirit comparable in its value and appeal to any others which could be mentioned. But this way of reproducing colour has its limitations. It is laborious and time-consuming, and the excellence of the final product is a highly variable and uncertain quantity. Further, when a picture has been painted which has an enduring value, those who wish to see it have to travel—if necessary to the other end of the earth—to the place where it has found a resting place.

The foregoing is an attempt to explain the reasons why the reproduction of colour by quasi-mechanical processes has, at the present time, assumed an importance comparable with that of the closely allied art of printing. The development of the processes by which colour is reproduced has been essentially on an empirical basis in which trial and error have played the major role. Nevertheless, useful guidance has been forthcoming from experience gathered in other fields of activity in the production of colour, viz., painting and dyeing. To some extent also, it has benefited by the reported results of the studies on colour mixing made by physicists and others in the nineteenth century.

We shall here approach the subject of colour-reproduction from the new points of view indicated by the studies on colour described in our preceding chapters.

We shall choose a specific case of a physical phenomenon in which we observe colour and which has the merit that it can be called into existence exhibiting identical characters whenever desired. We then set ourself to the problem of how a picture of it can be made which can claim some measure of resemblance to the original.

The phenomenon which is here referred to is that of the colours of interference, the best-known example being that of Newton's rings as seen in white light under sufficient magnification. A detailed description of these rings has been given in an earlier chapter in which the highly important role played by the yellow sector of the spectrum in the effects observed has been clearly set out. The major feature of these rings is the fluctuations of luminosity which exhibit themselves as a regular succession of maxima and minima of illumination. The positions of these maxima and minima are determined by the wavelength of yellow light and this is shown by actual measurement of the positions of the minima of illumination to be $579\text{ m}\mu$. The minima of illumination are highly pronounced: in particular the first minimum is almost perfectly black, and the second minimum is also very dark.

If now it is proposed to produce a picture of the rings as we see them on a piece of white card with a small brush and using coloured inks of different sorts, it is evident that a minimum of *four* inks of different colours would be needed: black ink, yellow ink, red ink and green ink. The black ink would be needed for exhibiting the central black area in the ring system, and the first two or three of the minima of illumination which cannot otherwise be represented. The yellow ink would be needed to exhibit the colour of the brightest part of the first three rings in the pattern. The red and the green inks would be needed to represent the colours in the regions respectively preceding and following the circles of minimum illumination in the first few rings. They would also be needed to represent the alternations of colour perceived in the outer rings of the pattern.

It is obviously not an accidental circumstance that in the processes of colour printing, it is also customary to use four colours, viz., yellow, magenta, cyan and black in the order stated. Usually, the first printing is with the yellow ink, the second printing is with the magenta ink, the third printing is with the cyan ink, while the fourth printing is with black ink. The last printing completes the picture which would otherwise fail to exhibit the local contrasts in respect of brightness exhibited by the object itself.

Some remarks may be made here regarding the three coloured inks used in process-colour printing. White printed on with magenta ink may be described as exhibiting a colour which is predominantly red. But spectroscopic examination reveals that while the green and yellow sectors are both much weakened, the red sector is accompanied by the blue sector with quite appreciable intensity. Likewise, the cyan ink shows both the green and the blue sectors in great strength while the yellow and red sectors are both much weakened. A white surface which has been printed upon with yellow ink when examined spectroscopically shows that the observed colour is the result of the nearly complete extinction of the blue

sector, while the green, yellow and red sectors are all present in practically undiminished strength.

It is necessary to indicate how the four blocks used respectively for the four printings are prepared. The negative for the yellow printer is made by using a blue filter when photographing the object. Likewise, for the magenta printer a green filter is used and for the cyan printer, a red filter. For the black printer several alternative procedures are available, the simplest being the use of a yellow filter. The choice of the filter used in making the three colour-separation negatives is based on the idea that the colour which is transferred to the paper by the printer should be complementary to that transmitted by the filter used in making the negative.

It should also be mentioned that the printing blocks are prepared by the half-tone process. The cross-line screen used in the process results in the breaking up of the picture into thousands of dots of light of varying sizes. These dots would appear in the impressions recorded on the paper by each of the four printing blocks. It should be emphasised that it is not the intention that the sets of dots in the impressions left by the four blocks should be coincident. On the other hand, to avoid such coincidences as far as possible, the half-tone screens are set at different angles to each other, these being so chosen as to avoid the appearance of moire patterns or other objectionable features in the reproductions. To secure these results it is sometimes found desirable to use a different screen-ruling for the yellow plate than for the plates of other colours.

If, in the picture as finally printed, the dots of different colours do not actually overlap, the eye is presented with a mosaic in which areas of white, black, yellow, magenta and cyan of varying sizes are interspersed. It would evidently be not possible for the eye to take note of their individual presence and the visual impression would therefore be a synthesis in which the effects of the individual areas are integrated into a single sensation. This sensation would depend on the relative proportions of the five areas exhibiting different colours. As the absorption spectra of the three coloured inks are very different, we may expect that a wide range of colours would be exhibited in various cases.

When photographic reproductions in colour are viewed through a magnifier, the structures which appear in them as areas of colour are immediately recognisable. In some cases, they exhibit hexagonal outlines, in others they appear as squares. The sizes of the individual dots and the colours which they show can readily be related to the colour exhibited to the eye by the entire group. Where the colour is yellow or blue-green or magenta, the dots of those colours are naturally predominant. In areas exhibiting other colours, the presence of dots of two or three different colours is evident and their influence on the perceived colour is readily traceable.

Summing up, we may say that when we view a photographic reproduction in colour, in general we perceive hues which are not really there, but represent a

synthesis effected within the eye of the observer. The actual processes employed and especially the need for a fourth block which prints in black and white is a clear disproof of the idea that the reproduction of colour is based on the trichromatic hypothesis of colour perception.

The new physiology of vision—Chapter XXX. The photo-mechanical reproduction of colour

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We return to the subject of the reproduction of colour dealt with in the preceding chapter for a closer examination of the results achieved by the process most frequently employed for that purpose. As has already been there indicated, this operates on the same principle as that used for producing illustrations in black and white and known as the half-tone process. But instead of one half-tone block, the reproduction of colour is based on the use of four such blocks, the impressions of which are transferred to paper using four differently coloured inks, viz., black, yellow, magenta (also known as process red) and cyan (also known as process blue). The four blocks are individually prepared from four separate negatives obtained by photographing the objects under study through four different and appropriately chosen colour filters. It is of great importance to notice that the ruled screens used in making these photographs are set at different angles, viz., for example, at 45° for the black printer, at 75° for the magenta printer, at 90° for the yellow printer and at 105° for the cyan printer. As the result of these arrangements, the rows of dots of varying sizes which are transferred to the paper by the four printing blocks are orientated differently, as can be seen on examining the final printing through a magnifying lens.

A remarkable consequence of the arrangements described above is that the colours perceived by an observer are the impressions produced on his vision by a mosaic of differently coloured dots grouped around each other in a geometric pattern. These mosaics are visible in the finished picture on examination through a magnifying lens. That a great range of colours are thus successfully pictured is a fact of experience which evidently calls for further study and elucidation.

The reproduction of pictures in colour is a common feature in many publications of a popular nature. It is therefore easy for anyone to have access to a great mass of material illustrating scenes and objects of the most varied nature. A detailed study of such pictures through a magnifier makes it possible to arrive at definite conclusions regarding the manner in which the colours observed are related to the mosaic patterns appearing in the reproductions. Such a study demonstrates that the view commonly expressed regarding the reproduction of colour by the half-tone process, viz., that it is based on the subtractive principle of colour superposition, is completely false.

Comparative study of numerous cases makes it evident that the sensation excited by a mosaic of colour dots is determined by the proportion of the areas in it occupied respectively by the four coloured inks used in the printing and by the unoccupied area, if any, of the white surface of the paper. This conclusion emerges from a study covering the most varied examples of objects portrayed as well as of the colours displayed.

The colour most often represented in pictures is the blue of the sky. Depending on the circumstances, the colour thus depicted varies from a very light to a very deep blue, such variations often appearing in one and the same picture and not infrequently in areas adjacent to each other. In the areas depicting a blue sky, yellow dots do not appear at all and it is also unusual to find any dots of black ink. The colours that we do find in the mosaics representing a blue sky are cyan, magenta and white. In the more lightly coloured areas, the proportions of white to cyan is very considerable and of the magenta to cyan is generally small. In the bluer skies, the proportion of white to cyan diminishes and may even become negligible. On the other hand, the areas occupied by magenta are proportionately larger, and numerous cases are to be found in which we have only cyan and magenta, the areas occupied by these being comparable with each other.

Cyan ink printed on white paper exhibits both the blue and the green sectors in the spectrum of the light diffused by it, the yellow and red sectors being weakened and indeed nearly suppressed. On the other hand, magenta suppresses the green and the yellow and exhibits only both the blue and the red sectors in the diffused light. It is not surprising in these circumstances that since yellow is absent, blue is the dominant colour in the sensation excited by a mosaic in which cyan and magenta are both present; both green and red being much weakened are masked by the blue and are not perceived.

Of particular interest in this connection are the pictures of specimens of *lapis lazuli* found in Afghanistan which will be found reproduced on page 434 of the *Geographical Magazine* for October 1965. Sixteen specimens are shown grouped together, their hues ranging from a light blue to a dark blue approaching violet in colour. The greenish-blue dots of cyan ink can be recognised in the reproductions of all the specimens, even in those which seem to the eye to be dark blue in colour. The spots of magenta ink are also visible, but they are not very conspicuous. It is evident that the black printer has played a highly important role in the representation of the specimens which exhibit darker hues. Indeed, these pictures suggest that a greatly diminished brightness of the mosaics is itself the reason why the blues are perceived as being of darker hues approximating to violet in colour.

The dominant colour of vegetation is green and it figures very prominently in pictures of gardens and parks. The shade of colour varies from a light green in the case of freshly-grown grass to a deep green in the mature leaves of well-grown trees. Cyan and yellow are the prominent features in the areas of mosaic which appear green in the pictures. The greater the proportion of yellow to the cyan, the lighter is the green colour which is perceived. These results are intelligible, since

cyan ink exhibits both blue and green strongly while weakening the yellow and the red. On the other hand, yellow ink extinguishes the blue while the rest of the spectrum is perceived including especially the yellow. In the resulting sensation, therefore, the green is dominant. The more completely the yellow and red are suppressed by the cyan, the deeper would be the green exhibited by the mosaic.

Pictures in colour of well-known personages are very popular. The chief interest in such pictures is, of course, the individual himself, including especially the contours of his face, his complexion, the colour of the eyes and other important details. These features differ widely from individual to individual. Certain general characteristics may, however, be recognised. In a great many cases, magenta and yellow are the principal colours noticeable in the mosaics appearing in the reproduction of the faces. The more suntanned the complexion is, the greater is the proportion of the magenta to the yellow. In the darker areas, the yellow is replaced by black, and a sprinkling of cyan is also noticeable. Indeed, the examination of portraits reproduced in colour furnishes a highly instructive demonstration of the role played by the mosaics of colour spots in determining what we perceive in the pictures.

Brightly coloured dresses form an attractive feature in pictures of assemblies or public gatherings. Examination of such pictures is a convenient procedure for ascertaining how the proportion of the inks present in the mosaics determines the perceived colour. Taking, for instance, the brilliantly coloured tartans exhibiting stripes of colour which are a familiar feature in pictures of Scottish assemblies, one can trace the colour composition of each individual stripe as reproduced in the half-tone picture. In the orange-coloured stripes, the mosaic consists of rows of yellow and magenta crossing each other, these occupying approximately equal areas. In the red stripes, we have also a mosaic of magenta and yellow, but the magenta is then preponderant. In the green stripes, we have mosaics of cyan, yellow and black, and in the blue stripes, mosaics of cyan, magenta and white.

The reproduction of floral colours by the half-tone process is a subject in itself. Flowers being the principal adornment in public parks as well as of the gardens attached to private houses, they are favourite subjects for colour photography as also for pictures to illustrate publications dealing with various aspects of town and country life. There is a further reason for the great interest shown in reproducing pictures of flowers. A great industry has grown up devoted to the production and marketing of flowering plants and especially new varieties thereof. Colour plays a highly important role in the selection and popularity of the new varieties, and horticulturists are therefore at great pains to produce literature in which the nuances of colour of their productions are accurately displayed.

As an illustration of the foregoing remarks, we may mention a recently published pocket encyclopaedia of roses in which no fewer than 421 varieties of roses have been illustrated in colour, together with their origins and pedigrees and a detailed description of the blooms. The colours of the roses have been

classified into nine distinct groups. A systematic examination of all the pictures reproduced in this publication showed that in all except three cases, the colour mosaics showed only three inks, viz., yellow, black and red, besides white areas. The three exceptions were roses which displayed lilac coloured hues, the distinctive colour being evidently due to the presence of cyan as one of the components in the mosaics.

The new physiology of vision—Chapter XXXI. The integration of colour by the retina

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In the preceding chapter, it has been demonstrated that the successful reproduction of colour by the well-known half-tone process is made possible by the remarkable power of our eyes to integrate the impression produced by a mosaic of spots of different colours into a single colour determined by the areas occupied respectively by the different colours in the mosaic. In a general way, anyone can satisfy himself of the correctness of this statement by a simple inspection through a magnifying lens of a few half-tone pictures in colour. In the last chapter, a sufficient number of examples have been set out which illustrate this situation. We return to the subject for the reason that the integration of colour by the retina is a fact of great scientific interest. Ample material is forthcoming not only to demonstrate the phenomenon but also to place it on a quantitative basis. Further, it can also be observed by using entirely different techniques which reveal other features of interest.

Insect colours: In the *National Geographic Magazine* some years ago, an article appeared under the title "Insect Rivals of the Rainbow" containing pictures of no fewer than 263 insects of various sorts which were reproduced in 24 colour plates. In the same magazine in another issue, an article, under the title "Strange Habits of Familiar Moths and Butterflies", was illustrated by pictures of no fewer than 162 species of moths and butterflies in 15 colour plates. The range of hues covered by these illustrations is very great. Hence these reproductions are valuable as an aid to the study of the relationship between the mosaics of colour and the visual impressions which they produce.

As has already been set out in the preceding chapter, the representation of colour by the half-tone process is achieved by the use of just four printing inks, viz., black, yellow, magenta (or process red) and cyan (or process blue) on white paper. If we assume the total available area of a given mosaic to be divided into 16 equal parts and the parts filled by the four inks range in number from 0 to 16, (the total, of course, should not exceed 16, the unfilled part being white) the number of the different possible colours thus resulting would be quite large. Even only binary combinations, e.g., yellow and white, magenta and white, cyan and white,

yellow and black, magenta and black, cyan and black, yellow and magenta, yellow and cyan, magenta and cyan, would give us great number of different hues. Examining the insect pictures through a magnifying lens, each of these binary combinations and the characteristic hues which they generate can be recognised in individual insects or in the individual areas of colour displayed by them. We shall content ourself with a few selected examples.

We may begin with some strong colours. The red areas are represented by magenta ink and appear of a deeper and darker hue when a substantial proportion of magenta is replaced by black. Various shades ranging from a bright yellow to a deep orange are exhibited by mosaics of which the areas are occupied by yellow and magenta inks in different proportions. Various shades ranging from a bright green to a greenish-blue are exhibited by areas of which cyan ink occupies a substantial part, the rest being occupied by yellow ink. Various shades ranging from a bright blue to a deep purple are exhibited by mosaics occupied by the cyan and magenta inks in varying proportions. If, in addition, areas of black ink are present, the colours appear to be of a deeper and darker hue. *Vice-versa*, if areas of white are present, the colours are lighter and brighter.

Interference colours: Excellent illustrations of the manner in which our eyes integrate colour-sensations appearing in areas which are contiguous are furnished by the colours of thin films. Reference has already been made in an earlier chapter to the remarkable fact that when Newton's rings are formed between two plates of glass, one of which is flat and the other has a radius of curvature of 3.6 m, the interference pattern exhibits no colour at all when viewed from the usual distance of distinct vision, even though the rings are themselves seen quite clearly. The pattern occupies an area of over one square cm and what is actually visible is a dark central patch surrounding which appear a succession of bright and dark rings, some six or seven in number, which approach more closely as we proceed outwards. Viewed under a low magnifying power a few more rings can be seen and counted in the pattern, but the pattern remains achromatic. To observe colour, the interference pattern has to be viewed from close quarters using fairly high magnifying powers. All the rings then show brilliant colours.

Newton's rings can also be observed on a much smaller scale using surfaces of which the radii of curvature are not large. In such cases, even merely to see the rings, we require a fairly high magnification, and it is to be remarked that the colours in such cases are scarcely noticeable. The greater the magnifying power employed, the more clearly are the colours seen.

By using two glass plates which deviate from planeness by a very little, Newton's rings can be obtained on such a large scale that brilliant colours are exhibited and are conspicuously visible without any optical aid. Likewise, using two circular disks of optically plane glass, a wedge-shaped air film may be obtained between them by exerting pressure at the end of one common diameter while leaving the other end free. The straight fringes exhibited by such films being

on a large scale, a brilliant succession of colours is exhibited by the film. A comparative study of such interference colours when viewed from various distances is particularly instructive.

The colours of Newton's rings even observed on a large scale disappear from view when viewed from a distance of a few metres, the pattern then appearing achromatic. This change is not sudden but progressive and can be followed step by step as the distance of the ring pattern from the observer is increased. Remarkably enough, the colours which first cease to be observed are those of the rings immediately surrounding the first dark minimum. The colours of the outer rings which are narrower nevertheless continue to be visible till the observer has moved much further away. Finally, these also appear achromatic.

The straight fringes of a wedge-shaped film behave rather differently. The spacing of the fringes makes a much closer approximation to uniformity than is the case with Newton's rings. The fringes of higher order are thus of about the same width as those of lower orders. Here again, we find that it is the fringes of lower order that cease to exhibit colour first as the distance of the observer is progressively increased. The colours of higher orders on the other hand show a less rapid weakening and indeed they continue to be recognisable so long as the rings themselves can be discerned.

Still another type of behaviour is shown by films of which the interferences of higher orders are enclosed by those of lower orders and are more widely separated than the latter. Such films can readily be obtained by clamping two thick plates of glass together at their edges. At close quarters, the interferences of all orders show brilliant colours. As the observer moves away, the fringes of lower orders lose colour and become achromatic and they are followed in succession by those of higher orders. But the central fringe of highest order which is very broad continues to exhibit brilliant colour even when the observer is far away from the glass plates.

It is clear from these facts of observation that the replacement of the individual colours in a given area by an integrated colour-sensation manifests itself only when the angular dimensions of the area as perceived by the eye are small enough. It is also significant that differences in luminosity continue to be observed when differences in colour cease to be perceived. That there is a relationship between the effects now under consideration and the phenomena of visual acuity is thereby made evident. But what exactly is the nature of such relationship requires further elucidation.

A further question arises in regard to the precise nature of the colour synthesis which is effective when a mosaic of areas exhibiting different colours comes under observation. So far as the present observations go, it would seem that the general ideas which emerged from the studies on the visual synthesis of colour described in earlier chapters are valid also in the present context.

The new physiology of vision—Chapter XXXII. Defects in colour vision

SIR C V RAMAN

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John Dalton who in his later years achieved fame as the founder of the atomic chemical theory presented in October 1794 a communication entitled “Extraordinary facts relating to the vision of colours” to the Manchester Literary and Philosophical Society. This was published in the Memoirs of that Society in the year 1798. The observations on which Dalton’s memoir was based were those of his own visual deficiency and that of his brother in the perception of colour. Dalton said that he could distinguish in the spectrum two hues which he called yellow and blue, his yellow embracing the red, the orange, the yellow and the green of normal subjects, while his blue appeared in the part of the spectrum which follows the green; he said further that the colour described by others as the violet which appears at the end of the spectrum seemed to him to be a little different from the blue perceived by himself, being more saturated in hue.

Dalton’s scientific analysis of his own personal colour perceptions laid the foundations of a subject the literature of which received vast accretions in subsequent years. The measure of attention devoted to the topic is ascribable to the interest attaching to it from diverse standpoints. The defects in colour vision described by Dalton were clearly not in the nature of a disease. They are congenital in character and are acquired by inheritance from or through the parents of the person exhibiting them. Numerous studies made on this aspect of the matter have shown that the deficiencies are far more frequent in men than in women and are indeed comparatively rare in the latter cases. Daltonism (by which name the phenomenon is still frequently referred to) may be exhibited by men to the extent of two or three per cent of the male population. The predominance of the males in this respect is explained by the laws of heredity: anomalies of colour vision are transmitted by the chromosomes which determine the sex. In the case of a man, if a single chromosome X carries the defect, this is sufficient to make his vision abnormal, but with the woman both the X chromosomes must be affected before the infirmity shows itself; otherwise, the woman acts simply as a carrier and transmits the defect without exhibiting it herself.

In our daily life and activities, the ability to distinguish between colours such as red, yellow, green and blue is extremely useful. There are various occupations in which the ability to recognise such colour differences is essential. Then, again, there are specialised activities in which the capacity for recognising the finer nuances of colour is extremely important. Considering all these circumstances, it is scarcely surprising that much attention has been devoted to the subject of colour discrimination as affected by the presence of defects and anomalies in colour perception. Numerous tests have been devised for the evaluation of the ability to perceive colour differences, and for the detection and classification of the various cases in which it is not so high as it normally is.

The tests for "colour-blindness" commonly in use at the present time are charts from which the person examined is asked to read out numbers which appear as arrays of coloured dots interspersed amongst dots of other colours. The colours employed are, of course, not pure spectral colours, but are of various hues and shades. The sizes of the dots, the colours in which they are printed, the way in which they are arranged, the distance from which the observer is asked to view the charts, as well as the strength and colour of the illumination employed, all play a significant role in these tests. Hence, the exact significance of the tests and even their actual usefulness are matters needing consideration.

A third reason why daltonism and other types of deficiency in colour perception have attracted much attention is the bearing of the subject on the fundamental aspects of the physiology of vision. The following questions arise. What exactly is the nature of the differences between normal and defective colour perception, and how do these differences arise? In seeking for answers to these questions, it is clearly desirable that we simplify the issues as much as possible. We may do so by limiting ourselves to the case of the pure spectral colours, deferring the more complex problems of the perception of polychromatic radiation for consideration at a later stage. We may further limit ourselves to the case of daltonism, leaving aside other known types of defect or anomaly in the perception of colour which may be regarded as of lesser importance. These may be conveniently discussed after the characteristics of daltonism have been fully explored and elucidated.

The nature and origin of daltonism: The purpose of the present chapter is to describe new methods of study in this field and to discuss their results and their significance. We may, however, usefully begin by asking ourselves what the acceptance of Dalton's descriptions of his own colour sensations would imply in relation to the fundamental problems of colour perception. What Dalton perceived in the sector of the spectrum which we have designated as the blue sector was obviously not different from that experienced in that sector by normal observers. In the parts of the spectrum which we have designated as the red, yellow and green sectors and in which normal observers perceive these different colours, Dalton perceived only one colour termed by him as yellow. If we assume

that Dalton's yellow is the same as that perceived by normal observers in the yellow sector of the spectrum, important consequences would follow. In the first place, since the sensations of green and of red were not experienced by Dalton, his yellow could not possibly have been the result of a superposition of the green and red sensations. We are thus forced to concede that yellow is a sensation which has its own independent origin. Further, since yellow is a highly luminous sensation, it can claim to be regarded as being of major importance, while red and green are only auxiliaries which can be left out without any serious impairment of the other visual faculties.

The observational evidence already on record supports the views regarding the nature and origin of daltonism set forth above. The test charts for "colour-blindness" which are commercially available contain as the first of the series, one in which the number 12 is pictured by an array of dots of orange hue, surrounded by a field filled up with dots of a pale blue colour. This chart is read correctly and without the slightest difficulty or hesitation by all subjects, both normal and "colour-blind". This indicates that though "colour-blind" persons may confuse red and green, the blue and yellow are never mistaken for each other. In other words, blue and yellow are basic colours alike for normal persons and for the "colour-blind".

Further striking evidence that blue and yellow are perceived alike by normal and by "colour-blind" persons is furnished by the published studies of the so-called "unilateral colour-blindness". There have been quite a few cases which have come to notice and in which colour-deficiency is much more marked in vision with one eye than with the other. In such cases, it is evidently possible for the person concerned to compare the colour-sensations experienced by him with his two eyes. It has been reported that in all such cases, blue radiation at $450\text{ m}\mu$ and yellow radiation at $575\text{ m}\mu$ exhibit colours which are not different as seen respectively with the two eyes. Dalton's description of the two-colour spectrum thus receives an impressive confirmation.

The colours of interference: The author has devised a new method for the study of "colour-blindness" which enables the sensations of normal observers to be quickly compared with those having defective colour-vision. The person whose vision is under study is asked to view a pattern of interference colours as seen with white light and to describe in his own words what he observes. For this purpose, the most suitable set of interference colours are the well-known rings of Newton but produced on a much larger scale than usual so that no optical aid is needed to observe them and examine their characteristics. Such rings can be produced by placing two fairly thick plates of glass in contact with each other in an appropriate orientation. They are seen by reason of the fact that such plates, though intended to be quite flat, actually exhibit over extensive areas a cylindrical curvature of very large radius. The geometry of the interference pattern exhibited by the air film enclosed between two such plates is determined by their relative

orientation. The fringes appear as straight lines when the axes of the cylindrical elevations on the two plates are parallel to each other; they appear as elliptic rings when these directions are inclined and as circular rings when they are exactly in the crossed positions. Circular ring-patterns exhibiting brilliant colours and covering an area $5\text{ cm} \times 5\text{ cm}$ may thus be readily obtained.

The appearance of such interference patterns as seen by an observer with normal vision has already been described in an earlier chapter. The significant feature is that the pattern exhibits fluctuations of brightness as the principal feature and these are accompanied by colours which arise as incidental consequences of the variations of luminosity in the field. Measurements of the positions of the minima of brightness in the pattern as observed with white light agree with the positions of the minima of brightness in the same interference pattern observed using monochromatic illumination of wavelength $579\text{ m}\mu$. For an observer with normal vision, the first few rings exhibit the successive minima of illumination very conspicuously, while the outer rings appear as circles of colour which are alternately red and green.

The interference pattern as seen by an observer with normal colour vision, may therefore be described as a pattern of fluctuating brightness due principally to the yellow sector of the spectrum, accompanied by fluctuations of colour in which the red and green sectors manifest themselves visibly in the neighbourhood of the regions where the yellow has the minimum luminosity. It is evident that in these circumstances, the pattern would present a very different appearance to a person with normal colour vision and to one who is unable to perceive the red and the green of the spectrum.

Colour and luminosity in the spectrum: Another method for testing colour vision is for the person under study to be presented with the spectrum of a very brilliant source of white light appearing on the ground-glass screen of a constant deviation spectrograph, arrangements being made to vary the brightness of the spectrum over a wide range of values. The subject is asked firstly to describe in his own language what he observes on the screen. He is also asked to indicate with a pointer, the exact points at which the spectrum appears to him to commence and to end, the positions where the colour in the spectrum as seen by him appears to alter, and the position or positions in the spectrum which appears to him to exhibit the maximum luminosity. These tests may be made at three different levels of spectral luminosity, one of which is very low, another medium and a third which is quite high. The low-intensity spectrum may be obtained by interposing an opal-glass sheet between the source of light and the slit of the spectrograph, while the medium and high-intensity spectra are obtained without the opal-glass sheet, by merely moving the spectrograph from a distant position to one much nearer the source of light.

The tests described above are very simple and can be very quickly made. They may be usefully preceded by even simpler tests, such as asking the subject to name

the colours of variously brightly hued plates shown to him, then asking him to read the numbers on the test-charts of the usual kind and also to notice and name the colours of the individual dots appearing on such charts.

Results of the tests: We proceed to describe the observations reported by a person who will be referred to here as C D. He was a competent man of science and could therefore be trusted to state accurately what he himself observed. Without any hesitation, C D correctly named the colour of a yellow cardboard box shown to him. He immediately recognised the number 12 on the first sheet of the test-chart printed as a set of orange dots which were surrounded by a field of pale blue dots. But the other sheets of the test-chart conveyed nothing to him. When the coloured rings of the interference pattern were presented to him, he had no difficulty in counting the number of rings visible in it, which he gave as seven. But the rings appeared to him to be yellow in colour, presenting the same hue as the cardboard box mentioned above; the successive rings appeared to him to be separated from each other by darker circles. He also noticed that indications of blue appeared in the first two or three rings of the series.

C D also placed the commencement of a spectrum of moderate or high luminosity at the long-wave end precisely where it is placed by an observer with normal vision. But he described the parts of the spectrum where a normal observer sees red, orange, yellow and green as being yellow in colour. He also placed the point of maximum luminosity in the spectrum at the same point, viz., $579\text{ m}\mu$ as an observer with normal vision. He observed the luminosity to fall off in the region of transition from green to blue as is also noticed by a normal observer. The blue of the spectrum was named by him as blue, and its termination as placed by him agreed in its position with that noticed by normal observers. The spectrum at the lowest level of luminosity did not appear to C D to exhibit colour at all, though to a normal observer, the green was quite clear. The red end of the spectrum had shifted towards shorter wavelengths, alike to C D and to an observer with normal vision. The point of maximum luminosity in the spectrum of low brightness had also shifted considerably towards shorter wavelengths and to the same extent for C D as to a normal observer.

It is clear from these observations that C D exhibited daltonism in a typical fashion. Further it is clear that his observations support the views regarding the nature and origin of daltonism set forth above.

The new physiology of vision—Chapter XXXIII. The testing of colour-vision

SIR C V RAMAN

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The lectures delivered under the auspices of the Indian Academy of Sciences on the 21st and 22nd December 1965 in the Chemistry Theatre of the Osmania University at Hyderabad were attended by the students of the University in large numbers. After the lectures given on the forenoon of the second day, there was an hour left free for other activities. The author decided to make use of this opportunity for an examination of the colour-vision of those who had attended the lectures. The suggestion met with an enthusiastic response. Those volunteering for the test moved to an adjoining lecture theatre which was much better lighted and the examination then proceeded.

The aim was, in the first instance, to pick out those whose colour-vision was defective and then to examine their colour sense in greater detail. The number of persons to be examined being large, the preliminary selection had to be made quite speedily. One after another, they were shown two sheets of a test-chart and asked to read the numbers shown therein. The first sheet contained the number 12 printed in orange surrounded by a field of dots of a bluish colour. The second sheet was selected at random from amongst those contained in the chart. All read the first sheet without any difficulty or hesitation. Those who read the second sheet shown to them without hesitation or error were also eliminated from the test. Only eight of the men students were thus left over and they were then tested more fully. It emerged that four of the eight chosen in the preliminary selection were not really defective in their colour-vision. The remaining four were then more carefully examined. They will be referred to in what follows as Suryan, Chandran, Shukla and Krishna respectively. These, of course, were not their real names.

Something should be said here about the nature of the charts used for the testing. Those were the well-known Ishihara Charts of which the 1958 edition was available containing 38 plates. Of these, only 25 are intended for general use. These again may be divided into five groups. Charts 2 to 9 are designed so that the numbers would be read wrongly by colour-blind persons, while charts 10 to 17 could not be read at all by them. Of the remaining charts, 22 to 25 are of special interest, as they have been designed to distinguish between three groups, “the

completely red-blind", "the completely green blind" and "the normal and incompletely red-green blind" persons from each other.

Suryan, Chandran and Shukla were unable to read charts 9 to 17. Krishna, on the other hand, could read some of them correctly, some incorrectly and others not at all. All four of them, however, had difficulties with charts 2 to 8. From these findings it was evident that while Suryan, Chandran and Shukla were definitely colour-blind, Krishna could not be definitely classed as such. Each of the four were then shown the two exhibits of interference colours and were given sufficient time to observe them carefully and to write down in their words what they could notice in them. This was done in a verandah, the exhibits being placed on a low parapet, so that the interference patterns could be seen by reflected sky-light incident nearly normally on the air-films exhibiting the colours. One of the exhibits was a set of circular rings of the well-known Newtonian type. But the air-film at the centre was not of zero thickness, so that a blue patch appeared at the centre of the pattern. This was surrounded by a ring of yellow beyond which again appeared other interferences exhibiting cycles of colour in which red and green were predominant, alternately following each other. The other exhibit showed the interferences in the opposite order. Red and green were the principal colours in the innermost region and they were followed by other colour sequences of the same nature as in Newton's rings. But the colour progression began at the outer margins where the interferences of lowest order were observed. In these latter regions, the fluctuations of brightness were the principal features of the pattern.

The weight to be attached respectively to the observations reported by the four observers depends on their ability to observe correctly and express themselves clearly and to some extent also on the extent of their experience of laboratory work. It should therefore be mentioned that Suryan had already taken his Bachelor's degree and was engaged in postgraduate studies in physics. Chandran had not yet taken his degree, but his record of observations is clear and systematic. Shukla and Krishna were both undergraduates.

Suryan described the Newtonian pattern as a succession of rings, beginning with blue at the centre and followed by yellow and by blue rings alternately. But he stressed the fact that the outer rings did not exhibit such full colours as the earlier ones and that the outermost rings could be described as being alternately dark and bright, the differences in brightness however not being much. Chandran reported observing that in the Newtonian pattern, the rings appeared as alternately violet and yellow, beginning with violet. He counted nine such rings in all and stressed the fact that the colours become progressively lighter as we proceed outwards in the pattern. Shukla also reported a succession of rings, of which he could see several. But he evidently found some difficulty in naming the colours which he observed. Krishna's descriptions of the Newtonian ring pattern resemble closely with that of a normal observer.

The reports of their observations by Suryan and by Chandran on the colours observed in the second exhibit of interferences agree closely. Near the margin of

the pattern where the interferences are of low order, they both reported that the rings appeared alternately yellow and blue. Suryan stressed that the yellow rings of low order appeared brighter than those of lower order. Shukla observed the succession of interferences but here again, he had some difficulty in naming the colours he observed. Krishna's description of this pattern closely resembles that of a normal observer.

Thus, the first two of the four subjects whose vision has been studied can be recognised on the basis of their own reports as cases of daltonism, in other words, as persons who observe a two-colour spectrum of yellow and blue. It would, of course, have been desirable to examine their ability to observe and distinguish colours in greater detail, using the methods described in the preceding chapter, viz., by exhibiting a spectrum of sufficient intensity on a ground glass screen and examining their perception of luminosity and colour in its different parts. But the opportunity for such examination did not exist in the circumstances of the case.

A few remarks may be appropriately made here regarding the manner in which a pattern of interference colours would present itself to the vision of a person whose colour sense is daltonian. In the case of a normal individual, the nature of the pattern is essentially that determined by the yellow sector of the spectrum, viz., a succession of maxima and minima of illumination whose positions are determined by the wavelength $579\text{ m}\mu$ in the spectrum at which the sensation is a pure yellow. The contrast between the maxima and minima would fall off progressively, but some five or six of each would be perceivable. Superposed on this pattern which would be of a yellow colour, appear the effects arising from the green and red sectors of the spectrum, and to a lesser extent also of the blue sector of the spectrum. The daltonian, on the other hand, would only perceive the blue sector of the spectrum, this appearing superposed on the effect of the yellow sector. The blue sector and the yellow sector would each individually exhibit a series of maxima and minima of illumination. But their superposition would result in the blue being visible only where it is very bright and the yellow is very feeble. *Per contra*, where the blue is very feeble and the yellow very bright, the latter colour alone would be perceived. Elsewhere, the superposition would result in effacing colour, but the maxima and minima of illumination due to the predominant yellow colour would continue to be observable. These consequences appear to be borne out by the observations by the two persons with daltonian colour sense reported above. So far as it is possible to draw any valid conclusions from the somewhat cursory studies which alone were possible in the circumstances, it would seem that both of them could be described as completely colour-blind, in the sense that they could not perceive either the red or the green colours which are such a conspicuous feature to a normal observer in the interference patterns.

The new physiology of vision—Chapter XXXIV. The nature and origin of defects in colour-vision

SIR C V RAMAN

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The studies described in the two preceding chapters provided an insight into the problem of explaining why certain individuals differ in their perceptions of colour from most other persons. At the same time, it became evident to the author that the new methods of study introduced by him in this field should be applied to more cases of the kind and carried out more exhaustively than was found possible in the examples first described. The present communication sets out the results of such a fuller study carried out in particularly favourable circumstances. It owes much to the co-operative spirit and scientific competence of the person whose colour-vision is here described and discussed in detail. He will be named here as Asoka which of course is not his real name. Asoka is a physicist of several years' standing with academic experience and had long been aware that his colour-perceptions are not of the normal kind. This fact came to his notice when he found that the $\lambda 5461$ radiation of a mercury lamp appeared to him to exhibit the same colour as the $\lambda 5770$ – 5790 doublet, whereas the first is usually described as green and the second as yellow.

The spectrum of white light from a brilliant source was focused on a ground-glass screen at the observing end of a glass spectrograph successively at three different levels of illumination, and Asoka was asked to indicate and describe what he saw in each case. Seen at the highest level of brightness, the spectrum appeared to him to begin at the long-wave end at about the same place as for a normal individual. But it commenced with an orange region and this was followed by bright yellow and then successively by a light blue, a dark blue and then violet. The change from yellow to blue appeared in the region when normal observers notice the change from green to blue. The short-wave end of the spectrum also agreed in position with those of normal observers. Asoka, when asked to locate the part of the spectrum which appeared to him to be the most luminous, put his pointer on the spot which appears yellow to normal individuals. At a lower level of intensity, the spectrum appeared to have become shorter at both ends, but the yellow part remained unaffected. At the lowest level of intensity which was attained by introducing a sheet of opal glass between the source of the

light and the spectrograph, only the part which appeared yellow in the first case could be seen, but it did not exhibit colour except at the long-wave end where it showed a weak orange tint.

Asoka was asked to hold a diffraction grating before his eye and to view through it, a slit between the two nearly-closed wooden shutters through which the light from the brilliantly illuminated sunlit sky found entry into the room. In the highly luminous first-order diffraction spectrum seen in these circumstances, Asoka reported seeing the colour sequence of red, orange, yellow, blue, indigo and violet. He could also see the Fraunhofer lines in the spectrum, as both the dispersion and resolution were adequate.

Asoka's colour perceptions were then tested by presenting to him in succession four different examples of interference patterns exhibiting colour and asking him to write down a detailed description of what he saw in them. The following is his description of a pattern of circular rings of the well-known Newtonian type. "The centre of the system is dark. This is surrounded by circular rings. The first ring is colourless. This is followed by (1) an orange, (2) deep blue, (3) orange, (4) light blue, (5) yellow, (6) light blue, and (7) light yellow. Beyond these rings, four alternate dark and colourless rings are also observed." Another pattern of the same type but on a slightly smaller scale was described by him as follows: "The centre of the pattern is dark. This is followed by coloured circular rings in the following order: (1) colourless, (2) deep orange, (3) deep blue, (4) orange, (5) light blue, and (6) light yellow. This is followed by three alternate dark and bright (colourless) rings."

The interference colours exhibited by a wedge-shaped air-film between two flat plates of glass was described by Asoka as follows: "The pattern consists of several bands more or less of uniform width. The band at the edge where the thickness of the wedge is minimum is dark. This is followed by (1) colourless, (2) red, (3) deep blue, (4) deep orange, (5) blue, (6) light orange, (7) light blue, and (8) very light yellow bands. This is followed by five alternate dark and bright (colourless) bands."

The fourth interference pattern was of a special type obtained by using two rectangular glass plates clamped together at the edges. This was viewed normally by reflected skylight incident on the plates in the direction of observation. Asoka described what he saw as follows: "The pattern consists of a central region which is light yellow surrounded by several ovals. Three of the ovals are alternately bright (no colour) and dark. The fourth one is orange followed by (5) blue, (6) orange, (7) deep blue, (8) deep orange, (9) deep blue, and (10) red ovals."

Commentary on the foregoing: Before reporting on further observations of other kinds by Asoka, we may usefully pause here to consider the significance of his descriptions of the interference patterns quoted above *in extenso*. They are remarkable in several respects. Firstly, they are totally different from the descriptions which would be given by a normal observer. Secondly, they report

the appearance of alternations of intensity without any manifestations of colour precisely in those regions of the pattern where a normal observer would report alternations of colour without alternations of intensity. Thirdly, they report alternations of colour in the regions where to a normal observer the major features which present themselves are the alternations of intensity. These features are a highly characteristic expression of the differences between normal and daltonian colour-vision.

The basis for an understanding of daltonian colour-vision is furnished by the fact emerging from studies with normal observers that the yellow of the spectrum exhibiting its maximum of luminosity at $579\text{ m}\mu$ plays the major role in their colour-perception, while the red and green observed on either side of the yellow in the spectrum are only subsidiaries or accompaniments of it. If, therefore, the red and the green sensations were left out, we would be left with the yellow and the blue sectors of the spectrum. This fits with Dalton's description of the colours in the spectrum as perceived by himself.

In the colours exhibited by interference patterns as seen by a normal observer, the fringes of higher order show bands of colours which may be described as alternations of red and green respectively. If these colours are not perceived, the same regions would exhibit the effects arising from the yellow and the blue sectors of the spectrum. The yellow being much the more intense may be expected to produce alternations of intensity in these regions. But the superposition of the effect of the blue sector would result in these alternations of brightness appearing more or less perfectly achromatic. This agrees with the observations of Asoka in all the four cases examined by him. In the interferences of lower orders, the alternations of intensity due to the yellow sector would be superposed on those due to the blue sector. These would not coincide with one another. Hence, in these regions, alternations of colour would be observed, the colours becoming progressively less saturated as we proceed from the lower to the higher orders of interference. This also agrees with the observations of Asoka.

A feature of special interest is the appearance of orange in Asoka's descriptions both of the colours of the spectrum as also of the interference patterns. That orange and yellow were perceived by him as distinct colours is clear from his recognition of these colours in various flowers shown to him. In particular, when shown the cluster of flowers of *Bignonia venusta* which he had not seen previously, he named their colour as orange without any hesitation. Since orange follows red in the succession of colours in the spectrum, this is an indication that the sensation of red was not completely absent in his perceptions of colour. It is noteworthy that in his description of the solar spectrum as observed at a high level of intensity, red does find a place. It also finds a place in his description of the fringes of lowest order in two of the interference patterns shown to him.

But on the other hand, there is evidence that his perception of red is much weaker than those of normal individuals. This is clear from his inability to read the test-chart No. 10 in the set published by the American Optical Company

(1940), which had evidently been designed to reveal such a weakness. In this test-chart, the numeral 9 is figured very conspicuously as a sequence of curiously shaped spots of a dull red hue, surrounded by spots of similar shape and printed in grey and black. The contrast of colours is very striking, but Asoka could not perceive it. A further indication of the weakness of his perception of red is the noticeable shortening of the spectrum at the long-wave end when its brightness is diminished.

Other observations: It may be worth listing here Asoka's readings of the test-charts commonly employed to reveal defective colour-vision. Both the Ishihara charts and those published by the American Optical Company exhibit as the first of the series, the numeral 12 in orange surrounded by a field of spot of a bluish colour. This is read without difficulty or hesitation alike by normal persons and by those with defective colour-vision. Charts 2 to 9 in the Ishihara set are designed so that persons with normal and defective colour-vision would read the numbers differently. Asoka responded to every one of them in the manner expected of one with defective colour-perception. He was unable to decipher the numbers appearing in Charts 10 to 17 and also in Charts 22 to 24 of the set of the Ishihara series.

Asoka was also presented with the test-charts published by the American Optical Company. This contained a set of 19 sheets. He did not succeed in reading the numerals appearing in Charts 2, 3, 6, 7, 8, 9, 10, 11, 14, 15, 16 and 17. But he read correctly and without hesitation the numerals appearing in Charts 4, 5, 12, 13, 18 and 19. It may be noted that these latter charts exhibit numerals printed in pale yellows and reds and surrounded by a field of dots of varying depths of green, or vice-versa. That he could do so indicates that his perceptions of red and green differed noticeably from each other.

Asoka was taken round the gardens of the Institute and asked to name the colours of various flowers shown to him. All yellow flowers were recognised by him as such without any hesitation; likewise, flowers with orange hues, viz., marigold and *Bignonia venusta*. The scarlet flowers of *Cordia sebestina* were described by him as red tending to orange. Various red and crimson flowers were named by him without hesitation as red and deep red respectively.

The deep blue flowers of the Morning Glory were named by him after some hesitation as violet in colour. The purplish-red flowers of the ground Orchid *Spathoglottis plicata* were also described by him as violet in colour. The flowers of the blue iris, and the pale blue flowers of *Plumbago capensis* were with some hesitation named by him as light blue.

His description of the colours of the bracts of different varieties of bougainvillea differed markedly from that of a normal observer. The light purple and the deep purple varieties were alike described by him as blue, while the rose-red bracts of another well-known variety were described by him as purple.

His naming of the colours of different varieties of pelargonium were not widely

different from those of normal observers. Remarkably enough, Asoka said he had no difficulty in recognising the green colour of leaves as such, provided they were deep enough, and not the paler hues often manifested.

Concluding remarks: Summing up, the colour perceptions of Asoka may be described as being approximately daltonian in character but not absolutely typical since his reds and greens were not wholly indistinguishable from each other. There are indications that Asoka's perceptions of red are much weaker and his perceptions of yellow much stronger than those of normal individuals.

The new physiology of vision—Chapter XXXV. The faintest observable spectrum

SIR C V RAMAN

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It is a noteworthy characteristic of human vision that it can function usefully and enable us to perceive objects illuminated by light at enormously different levels of brightness. The magnitude of these differences is indicated by a comparison between the illumination provided by the light of the noonday sun and the illumination received from the star-lit sky on a clear moonless night. Somewhere between these extremes is the illumination by the light of the full-moon shining in a clear sky. Astronomers rate the Sun as a star of magnitude—26·8 and the full-moon as a star of magnitude—12·0. These figures indicate that moonlight is about half-a-million times weaker than sunlight. Star-light is, of course, much weaker than the light of the full-moon. It has been estimated that the integrated light from the stars received at ground level is weaker than sunlight by a factor of three hundred million or thereabouts.

The question naturally arises whether the apparatus of human vision is the same and functions in the same manner over the whole of this enormous range of intensity of the light perceived by it. This is an issue of great importance and interest. The term “apparatus of vision” is here intended to refer not to any particular area in the retinae of our eyes, as for example, the foveal region, but to the whole of the retina or at least to the part of it that can be observed to function in wide-angle vision. A method of investigating this problem which suggests itself is to study the spectrum of white light over the whole of this range of brightness making use of a technique which enables us to perceive simultaneously the functioning of the foveal region and of the outlying parts in the retina. The present investigation describes such a technique and sets out the surprising results which have emerged from the studies made with it.

The technique of study: An extended linear source of light and a replica diffraction grating together make all the equipment that is needed for the purpose of the present study. The observer holds the diffraction grating close to his eye and views the line-source which may be at any convenient distance, the grating being held with its rulings parallel to the line-source. The observer's field of view will then include the line-source as well as the diffraction spectra of various orders

on either side of it. As the two diffraction spectra of the first order are usually much brighter than those of higher orders, the observer can view one or the other of those two spectra. Since the line-source may be of any convenient length, the spectrum under view will cover a great range of visual angles, both above and below the visual axis of the observer.

If the line-source is an elongated slit, it will be fully illuminated only if it is backed by an extended field of light. Hence, for such studies, a source of diffuse illumination covering the entire length of the slit is necessary. Since the aim of the investigation is to carry the study down to the lowest levels of illumination at which the spectrum can be perceived, it is necessary for the observer to be inside a completely darkened room and to remain there long enough to enable him to perceive the feeblest illumination. This may be for an hour or such longer period as may be found to be necessary. The only light which should find entry into the room is that passing through the slit under observation.

Two distinct choices are available for the light-sources to be studied. The first choice is that of the natural sources of diffuse light which are available over a great range of brightness, viz., the sun-lit sky in daytime, the progressively altering illumination of the sky during the twilight period, the sky illuminated by the light of the moon in its various phases, and finally the star-lit sky on a clear moonless night.

The other choice is that of artificial sources of light. As we are concerned with the spectrum of white light, we naturally choose a source emitting light at a high temperature and hence a source which is inherently of high luminosity. The question here arises of a procedure by which the light can be reduced to the lowest levels of luminosity, but without any change in its spectral character. The procedure which has been devised and which enables this aim to be realised is to allow a beam of light from a tungsten-filament lamp run at a high temperature to be diffused by a milk-white plastic screen, three such screens in succession being employed. The screens have polished surfaces which reflect a part of the incident light. But they are so placed with respect to each other that these reflections are not made use of, but only the light that diffused in directions other than that of regular reflection by the surface of the screen. The light is much enfeebled in this manner but without any change in its spectral character. By placing the three screens which operate by such diffusion at suitable distances from each other, the brightness of the light that is received and diffused by the third screen and thereafter passes through the slit under view by the observer is enormously reduced. It should be mentioned here that the luminosity of the spectra as seen by the observer is determined by the width of the slit and its distance from the observer. It can be altered through a great range of values by the observer approaching towards the slit or moving away from it.

Observations during twilight: To study the spectrum of skylight during the twilight period, the observer places himself at a distance of about three metres

from one of the windows of a room, all of which are covered by wooden shutters, but of which one can be opened a little so as to admit light from the sky through a narrow vertical slit about 150 cm in length. The opening of the slit can be varied, about a centimetre being the most suitable, though narrower slits can also be made use of. The resolution and dispersion provided by the diffraction grating in these circumstances is such that a great many of the Fraunhofer lines in the solar spectrum are clearly seen when the sun-lit sky is viewed through the slit by the observer with the grating held in front of his eye. To serve as a standard of comparison, a white diffusing screen of sufficient size is set up at a suitable distance so that it can be viewed through the slit. If the screen is lit up by direct sunlight, the solar spectrum seen by the observer exhibits the features characteristic of fairly high levels of brightness. The greatest luminosity is then in the yellow sector of the spectrum and the blue sector shows all its three different colours, viz., blue, indigo and violet in the order of diminishing wavelength.

In the latitude of Bangalore, the duration of twilight, in other words, the interval between the setting of the sun and the emergence of the fainter stars from the luminous background due to scattered sunlight is about an hour. During this period, great changes manifest themselves in the brightness of the part of the sky under observation. At the same time, however, the eyes of the observer seated in the dark room become enormously more sensitive to faint light. As a result, the slit continues to appear to be nearly as bright as before. But the spectrum of the light emerging through the slit is observed to alter in a remarkable fashion.

Four noteworthy changes may be noted in the appearance of the spectrum in the first half-hour of twilight during which the sky and the landscape illuminated by it both remain fairly bright. One of these changes is in the appearance of the blue sector of the spectrum. The bright blue which precedes the indigo and the violet in the spectrum disappears and is replaced by the darker indigo colour and this in its turn disappears, the "blue sector" then appearing of a violet colour throughout. A little later, the violet colour also fades away, but the "blue sector" continues to be distinguishable from the adjoining green sector by reason of its lack of colour and its much smaller luminosity.

A second noticeable change is in the location of the most luminous part of the spectrum. This exhibits a very definite shift, moving from the yellow sector into the green sector, in other words, from about 580 to about 550 m μ . But the green colour of the spectrum is the wavelength range between 500 and 560 m μ remains conspicuous. Indeed it appears distinctly more saturated than when the spectrum as a whole is highly luminous.

The third and indeed most striking change in the character of the spectrum is the progressive contraction and final disappearance of the red sector of the spectrum, in other words, of the part of the spectrum included in the wavelength range between 700 and 600 m μ . The longer wavelengths in this region are the first to become too feeble to be observed, despite the greatly increased sensitivity of the eye to dim light. When the visible end of the spectrum is at about 650 m μ , a

distinct change is noticeable in the colour of the region between 650 and 600 m μ . It then assumes a deeper red hue. Finally, the spectrum in this region becomes too weak to be observed and disappears from sight. This disappearance occurs long before the twilight illumination of the sky itself becomes unobservable, and while the landscape outside is still clearly visible in all its details.

The fourth and last change in the character of the spectrum is the weakening and disappearance of the yellow sector of the spectrum, in other words of the wavelength range between 560 and 600 m μ . The disappearance of the yellow closely follows that of the red sector. But when the red and yellow sectors are no longer observable, the green sector remains conspicuous. Thus, the spectrum of skylight in the latter part of the twilight period consists principally of the green sector in the wavelength range between 560 and 500 m μ , the maximum of luminosity being at about 540 m μ . This is accompanied by a weak extension towards shorter wavelengths representing the residue of the blue sector which remains visible at this stage.

It should be emphasised that the foregoing features are not in any way different in the different areas of the retina in which the spectrum is visibly manifested.

The spectrum of the star-lit sky: The disappearance of twilight from the sky is followed by a further fall in the intensity of the spectrum which nevertheless continues to be visible. All trace of colour having vanished, a method had to be devised to make it possible to ascertain the region of wavelengths in which the spectrum continues to be visible. This is accomplished by the use of a comparison spectrum of which the brightness is not so great as to disturb the sensitivity of the observer's vision but nevertheless allows spectral lines of known wavelength to be discernible. A white diffusing screen is placed below the level of the part of the sky under observation so that it can be seen through the same slit. This screen is illuminated by a beam of light from a distant mercury lamp or sodium lamp reflected by a system of mirrors. The characteristic lines of the spectrum of mercury or of sodium are then seen below and in a line with the continuous spectrum of the sky. The comparison spectrum could be switched off except when it is actually needed for locating the position and extension of the continuous spectrum which it adjoins.

From such observations, it becomes evident that the blue sector of the spectrum is not present in the spectrum of the star-lit sky. The limits of the part of the spectrum which continues to be visible can be determined by reference to the positions of the discrete lines of mercury and of sodium appearing below it. The yellow sodium doublet λ 5890–5896 is found to lie well outside the limits of the observable spectrum. Likewise, the violet line λ 4358 of the mercury arc lies outside of those limits. On the other hand, the green λ 5461 mercury line lies well within the region of the visible continuous spectrum. The yellow doublet λ 5770–5790 of mercury appears just outside the long wavelength limit of the sky-spectrum, while the weak λ 4916 of mercury appears close to its short-wave limit.

What is actually seen of the spectrum is thus confined to the wavelength range between 560 and 500 $m\mu$, the brightest part being at about 530 $m\mu$. These features are exhibited by the entire length of the spectrum covering the retina, irrespective of the particular part of it towards which the observer directs his vision.

The observations of the star-lit sky were made at various hours of the night when the sky was quite clear and free from haze or cloud, and the disturbing effects arising from the city-illumination were therefore at a minimum. The sky to the north of the Institute was made use of, since it was much better than the sky to the south in its freedom from such disturbance. No significant differences in the characters of the spectra could be noticed depending on the part of the sky under observation or on the time at which the observations were made.

Observations with artificial light-sources: The technique employed of such observations has already been described. It proved highly successful by reason of the fact that two dark rooms were available which were connected by a covered passage with two right-angle bends in it. It was possible, therefore, to place a brilliant source of light in one room without any light finding its way into the other room through the passage. The light diffused by a brilliantly illuminated screen placed in one room and then successively by two other diffusing screens placed at the two corners of the passage fell upon a slit placed near the entrance to the second room. This slit could be viewed by the observer through his diffraction grating.

The slit employed was 2 mm wide and 30 cm long and the observer could vary his distance from it to any extent desired. The observed luminosity of the spectrum could thus be varied over a great range of values. A further means of controlling the luminosity of the observed spectrum was by altering the illuminated area of the first diffusing screen. This area could be reduced from a circle of 40 cm diameter down to a circle of 6 cm diameter, thus allowing a reduction of luminosity by a factor of about 50.

The changes in the character of the observed spectra resulting from each step-down in the level of illumination could be made evident by replacing each diffusing screen by a reflecting mirror, thereby resulting in a great increase in the brightness of the illumination reaching the slit. The determination of the wavelength range in which the spectrum continues to be observable at the lower levels of illumination is effected with the aid of the discrete lines in comparison spectra of low intensity viewed through the same slit for a brief period of time sufficient to enable the observer to fix their positions.

Results of the investigation: The results of the study made with artificial light-sources are in full agreement with those described above using skylight at various levels of illumination. We may now sum up the conclusions reached. The spectrum of white light consists of four sectors, the wavelength ranges in which they appear being respectively from 400 to 500 $m\mu$ for the blue sector, from 500 to

560 $m\mu$ for the green sector, from 560 to 600 $m\mu$ for the yellow sector and from 600 to 700 $m\mu$ for the red sector. At high levels of illumination, the yellow sector is the most conspicuous, the red, green and blue sectors following it in that order. When the level of illumination is lowered sufficiently, the red sector is the first to pass out of sight, and is then followed by the yellow sector. At the lowest levels of illumination, the blue sector also disappears, till finally we are left only with the green sector covering the wavelength range from 500 to 560 $m\mu$. It then exhibits no observable colour, but the maximum of brightness is at about 530 $m\mu$. Thus, it is this restricted range of the spectrum which actually enables us to perceive and recognise the most dimly illuminated objects. This statement is valid alike for the fovea and for the outlying regions of the retina, there being no noteworthy differences between them at such levels of illumination.

Some remarks are here called for regarding the so-called "visual purple" which has in the past been identified as the material present in the retina that enables dim light to be perceived. The absorption spectrum of "visual purple" has been studied by several investigators. It exhibits a maximum of absorption at 500 $m\mu$, the absorption diminishing to smaller values both at higher and lower wavelengths. The absorption covers the entire range of wavelengths from 600 to 400 $m\mu$, and should therefore be effective in the perception of the yellow, green and the blue sector of the spectrum. The behaviour of "visual purple" thus inferred is wholly different from the characteristics of human vision at low levels of illumination established by the present investigation. It would seem, therefore, that the identification of the "visual purple" as the material which makes vision possible at such low levels is a misconceived idea.

One need not doubt that the "visual purple" is actually present in the living retina and that it subserves some physiological purpose. This purpose may be that of a protective material for preventing damage to the delicate structures of the retina by the incidence of strong light, especially in the region of shorter wavelengths. The photochemical decomposition of the material by strong light and its reconstitution in dim light may, in fact, be the means by which this protective action is brought into play.

The new physiology of vision—Chapter XXXVI. The postulated duality of the retina

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The facts of observation set out in the preceding chapter lead us to make a critical examination of the belief, firmly held by physiologists at the present time, that the human retina exhibits a duality in its structure as well as in its functioning. This belief finds concrete expression in the distinction drawn between two types of vision which are termed respectively as “Photopic Vision” and as “Scotopic Vision” and which are assumed to exist and to be distinguishable from each other. While “Photopic Vision” is effective at the higher levels of illumination, “Scotopic Vision”, as its name indicates, functions at the lowest levels. “Photopic Vision” alone exhibits differences of colour, while “Scotopic Vision” is achromatic. The acuity of vision is high in “photopic vision” and is almost non-existent in “scotopic vision”. To give plausibility to these beliefs, it is suggested that “photopic vision” may be identified with “cone-vision” and “scotopic vision” with “rod-vision”. So strongly are these beliefs entrenched in the literature of the subject that it may come as a surprise to the reader to be informed that the purpose of the present chapter is to demonstrate that the supposed duality of the human retina is a myth and that the ideas regarding human vision which rest on the assumption of such duality are altogether erroneous.

The falsity of the postulate: We may begin by pointing out that the differences in the characteristics of human vision at high and at low levels of illumination which have been sought to be interpreted as a consequence of the rod-cone duality of the structure of the retina have, in reality, an altogether different origin. It will suffice to point out that in all critical observations we naturally make use of the foveal region of our retinae, and these regions, as is well-known, contain only cones and no rods. Nevertheless, the fading away of colour and the loss of visual acuity which are associated with low levels of illumination are conspicuously evident in such observations. If, for example, the Great Nebula in Orion is viewed through a pair of binoculars, it appears as a luminous cloud without a trace of colour. On the other hand, seen through the great telescopes of the world, it appears as a vast area exhibiting resplendent colours.

Elsewhere than in the fovea, the rods and cones appear interspersed in the

retinal structure. It may therefore be taken for granted that the characteristics of human vision are determined by the rods and cones functioning jointly and not independently. Indeed, the assumption that rod-vision and cone-vision function independently of each other is ruled out by various facts of experience. We may here, for instance, recall the studies of the half-tone process of colour reproduction set out in an earlier chapter. It emerged from those studies that the retina integrates the different colours incident on it in adjacent areas and perceives them as a single resultant colour.

From the known fact of observation that fainter objects appear distinctly brighter when seen by averted vision than when viewed directly, we infer that the rods are more sensitive as detectors of radiation than the cones. This indeed becomes evident when a very faintly illuminated screen of plastic material which diffuses the light incident on it is viewed in a dark room. The marginal regions of the screen appear distinctly brighter than the central area. But the latter area continues to be perceived even at the lowest levels of illumination, thereby showing clearly that the fovea does not cease to function even in the dimmest light.

That the retina functions as a single unit and not as two retinae with different characteristics becomes even clearer when the observations set forth in the preceding chapter are recalled. An elongated slit backed by an extended source of light is viewed by the observer through a replica diffraction grating. Diffraction spectra having the same length as the illuminated slit are then seen in the field of view of the observer going right across the retina of the observing eye. When the luminosity of the source behind the slit is varied, the character of the spectra also alters. This is a demonstration that the so-called "luminous-efficiency" of radiation is itself dependent on the intensity of the light under observation. It alters progressively as we proceed from high to low levels of illumination. What is particularly significant is that these changes are not observably different for the different parts of the retina on which the spectra fall with the arrangement described.

Very significant also are the changes noticed and described in the preceding chapter in the character of the spectrum of white light as we proceed towards low levels of illumination. In succession, the red sector, the yellow sector and the blue sector of the spectrum pass out of sight, till, finally, only the green sector in the wavelength range between 560 and 500 $m\mu$ survives. It is this part of the spectrum which enables us to perceive light at the very lowest levels of brightness. It is evident that these faintest observable spectra bear no resemblance to the "scotopic spectrum" which has been described as covering the entire range of wavelengths from 400 to 700 $m\mu$ and as exhibiting the "maximum luminous efficiency" at the wavelength of 500 $m\mu$ or thereabouts. The inference is that the "scotopic spectrum" is an artificial concept which has no real significance in relation to the facts of human vision. We are also justified in inferring that the "visual purple" which has an absorption spectrum extending over the entire

wavelength range from 400 to 650 $m\mu$ does not function as the visual pigment which enables us to perceive light at low levels of brightness.

We proceed now to describe the results of some further experimental studies designed to carry the investigation of the visual perception of light in the various parts of the spectrum down to the lowest levels of illumination.

Techniques of study: We shall begin with the description of an experimental arrangement which enables an observer directly to view a spectrum at levels of brightness which can be progressively altered from high values down to the lowest levels till we reach the threshold of human vision at which light ceases to be visible. The apparatus is essentially a prismatic spectrograph of substantial dimensions but with a rather small dispersive power. Special devices enable the brightness of the spectrum as perceived by an observer to be varied over a great range. The collimator is a telescope with a 3-inch objective which has a focal length of 4 feet; the eye-piece is removed and replaced by a spectrometer slit. The light from the collimator passes through a 30° prism of dense flint glass with a square face 3 inches in height and in breadth. The light dispersed by this prism enters the observing telescope which has an objective of 6 inches diameter and a focal length of 13 feet. Between the prism and this objective is placed an iris-diaphragm, the diameter of which can be progressively reduced from a maximum of 4 inches down to a minimum of $\frac{1}{8}$ th of an inch, thereby reducing the area of the opening to 1/1000th part of its maximum value.

The maximum brightness of the spectrum is obtained when the source of light is held close to the slit. By increasing the distance of the source from the slit, this brightness can be diminished. To obtain a further large step-down in intensity, the light from the source is first allowed to fall on a diffusing screen of milk-white plastic material, instead of falling directly on the slit. The light diffused by the screen then enters the slit of the spectrograph. Likewise, instead of the observer viewing the spectrum directly, a milk-white plastic screen is placed at the focus of the 13-foot objective. The light reaches the screen and is focused on it. The spectrum appearing on the screen is visible to the observer by reason of the light diffused backwards by the surface. Thereby results a large reduction of its observed luminosity.

The entire apparatus and the observer himself are located in a large room which could be completely darkened. The source of light and the diffusing screen which illuminates the slit are both placed in a covered passage which leads up to the observing room. But no light is permitted to enter that room except that passing through the slit and spectrograph. The complete spectrum when formed on the viewing screen is about 10 cm long and about 2.5 cm broad. The observer remains in complete darkness for at least one hour before commencing his observations. He can view the spectrum either directly, or by averted vision if he so desires.

Observations with a mercury lamp: It is useful in the first instance to make use of a source of light exhibiting the discrete lines of the mercury arc on the background of a continuous spectrum. Such a lamp being available, when it is placed directly against the slit, the mercury arc lines λ 5790–5770, 5461, 4916, 4358 and 4046 can all be seen and recognised on the continuous background, provided the iris-diaphragm between the prism and the objective is fully open. When the iris is progressively closed down, the luminosity of the entire spectrum falls off, but to quite different extents in its different parts. In particular, the continuous spectrum seen in the red sector becomes weaker and finally disappears, the yellow doublet λ 5790–5770 becomes much fainter than the green line λ 5461, the continuous spectrum in the region of wavelengths less than λ 5000 ceases to be noticeable, λ 4358 becomes very weak and barely observable while the λ 4046 line completely disappears from sight.

If, instead of allowing the light from the lamp to fall directly on the slit, we use the diffusing screen as explained above, the brightness of the observed spectrum is greatly reduced. Even when the iris is fully open, all that can be seen of in the spectrum is the yellow doublet λ 5790–5770 and the green line λ 5461 of the mercury and a faint continuum covering the green sector of the spectrum upto about λ 5000. The yellow doublet is seen to be feebler than the green line. When the iris is closed down, the continuum disappears and both the yellow and green lines become very faint, the former much more so than the latter. Further reductions in the level of brightness may be effected by moving the lamp away from the diffusing screen. By increasing their separation from 15 to 150 cm, we lower the brightness by a factor of 100. In the spectrum as then observed, only the λ 5461 line is seen even when the iris is fully open. When the iris is progressively closed down, this line falls off in brightness and finally disappears from sight.

Observations with a source of white light: If instead of a lamp containing mercury vapour, we use a coiled-coil tungsten filament emitting light at a high temperature, its continuous spectrum is that of white light extending over the wavelength range from 700 to 400 $m\mu$. The alterations in the appearance of this spectrum as seen by the observer at various levels of brightness can be followed step by step in the same manner as described above in the case of the mercury vapour lamp. The red sector of the spectrum, the yellow sector and the blue sector each becomes progressively weaker and finally disappears from sight. All that is left of the spectrum is then the green sector in the range of wavelengths between 560 and 500 $m\mu$ with very feeble extensions on either side. These extensions also disappear until we are left only with a patch of light covering the green sector of the spectrum. The weakening and final disappearance from sight of this green sector is most conveniently produced by a progressive closing down of the iris-diaphragm separating the prism and the objective of 13-foot telescope. It is of

interest to note that the patch of spectrum when actually visible appears noticeably brighter when seen by averted vision than when directly viewed.

The spectra of the moonlit and starlit skies: A very convenient arrangement which enables an observer to view the spectrum of the faint light reaching the earth from various parts of the sky at night is for him to locate himself beneath the covered dome of an observatory of moderate size, e.g., one of 16-foot diameter. Seated on the floor of the observatory in total darkness, and holding a replica diffraction grating before his eye, he views the sky through the narrow opening, about an inch wide, left between the almost completely closed shutters which cover up the sky when the observatory is not in use. The diffraction spectra of the light entering the dome of the observatory through this narrow opening are seen projected against the inner surface of the dome as curved arcs of light on either side of the slit. They run parallel to each other and to the slit from end to end. The spectra of the first order are usually the brightest; one of them may be brighter than the other. It is noteworthy that the spectrum exhibits the same features over the entire length of it traversing the field of view of the observer, irrespective of the particular point on which the latter fixes his vision.

The brightness of the spectra as seen by the observer naturally depends on the circumstances of the case. If the sky is clear and is lit up by the light of the full-moon, the spectra are particularly conspicuous. But their features differ greatly from what would be seen in similar circumstances when the sunlit sky is observed. The width of the spectrum is much reduced and it can be readily ascertained with the aid of a comparison spectrum that the only part of it actually visible is confined to the wavelength range between 560 and 500 $m\mu$, in other words, the green sector. The red, yellow and blue sectors of the spectra are absent. Except that the spectra are less brilliant, precisely the same features are exhibited when the sky is clear and the moon is not full and hence the illumination of the sky by scattered moonlight is feebler. Indeed, the observations show that even when the moon is absent and the spectrum under observation is that due to starlight alone, the spectrum exhibits the same features though, of course, it is much less bright.

The new physiology of vision—Chapter XXXVII. The spectrum of the night-sky

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The major result which emerges from the investigations described in the two preceding chapters is that we are concerned with only one kind of vision and its variations in the entire range of illumination in which our eyes can perceive light. The differentiation made in the past between three distinct types of vision named as “photopic vision”, “mesopic vision” and “scotopic vision”, and functioning at different levels of illumination is shown by the factual results of the study to possess no valid basis or justification. In what follows, it will be shown that the characteristic features of human vision at low levels of brightness ascertained by spectroscopic methods and described in the two preceding chapters can be demonstrated in a very simple and striking fashion with the aid of appropriate colour filters.

On any clear moonless night, the light which reaches ground-level is principally that received from the stars overhead. Some of it comes from the very bright stars which are the most conspicuous objects in the night-sky. A substantial contribution is also made by the fainter stars of various magnitudes which can individually be perceived by an observer. Far more numerous are the faintest stars which cannot be perceived individually but which in the aggregate make a notable contribution to the observed luminosity of the sky. When these faint stars are present in great numbers in any particular area, e.g., in the Milky Way, the resulting diffuse luminosity of the sky is quite conspicuous. Nevertheless, except in the case of the very brightest stars, the luminous flux which reaches the eye of an observer from an individual star or from any limited area in the sky is extremely small.

That our visual perceptions are very different at low levels of illumination from what they are in bright light is made strikingly evident when the night-sky is viewed through a plate of glass which freely transmits light of wavelengths greater than $600\text{ m}\mu$ and is opaque to shorter wavelengths. Such a plate exhibits a bright red hue by transmitted light in day-time. Held against the night-sky, it resembles a sheet of black glass, completely obscuring both the individual stars and the general luminous background of the sky. Only the very brightest stars, viz., Sirius and a few others can be glimpsed through the filter as dim red spots of light. Quite

different, however, is the appearance in like circumstances of a disk of yellow glass which acts as a colour filter excluding light in the spectral range from 400 to 500 $m\mu$ and freely transmitting greater wavelengths. Held against the night-sky, the disk appears quite transparent and colourless. Neither the individual stars (except Sirius and a few others) nor the general background of the luminosity appears diminished in brightness when seen through the filter.

From the foregoing observations, it can be inferred that the part of the spectrum which makes a sensible contribution to the perceived luminosity of objects at low levels of brightness is limited to and falls within the range of wavelengths between 500 and 600 $m\mu$. We can go further towards fixing the part of the spectrum which functions in dim light by making use of colour filters which exclude both the red and yellow sectors of the spectrum and freely transmit the green and blue sectors. Such filters are readily prepared by staining gelatine films with an appropriate dye-stuff, e.g., cyanin, or disulphine blue. They exhibit a bright greenish-blue colour by transmitted light in day-time. But when held against the night-sky, the filters appear quite colourless and completely transparent. No noticeable reduction of brightness either of the individual stars (other than the most highly luminous) or of the background luminosity of the sky results from viewing them through the blue-green filters. Comparative study of the night-sky through the three different types of colour filter thus enables us to conclude that only the green sector of the spectrum, in other words, the wavelength region between 500 and 560 $m\mu$ is effective in the perception of light at the low levels of illumination with which we are concerned here.

The stated conclusion is confirmed by observations of the night-sky through colour filters of other kinds. Of particular significance is the fact that a filter of glass which transmits light only within the wavelength range between 400 and 500 $m\mu$, and accordingly exhibits a blue colour by transmission in daylight appears perfectly opaque when held up against the night-sky. Neither the individual stars—except a few of the highest luminosity—nor the general background of sky-illumination can be perceived through such a filter. A solution of cuprammonium in a flat-sided glass cell with its concentration adjusted to transmit the blue sector of the spectrum and absorb the rest exhibits the same behaviour. These observations establish that the blue region of the spectrum makes no sensible contribution to our perception of very feeble light-sources.

Colour filters of several sorts can be prepared with the aid of appropriately chosen dye-stuffs which completely eliminate the green sector, in other words, the wavelength range between 500 and 560 $m\mu$, while the other parts of the spectrum are transmitted more or less freely. For example, a gelatin film heavily dyed with methyl violet transmits light of a purplish-blue colour in which both the green and the yellow sectors are absent. Likewise, a filter dyed heavily with magenta cuts out the green and the yellow and allows the red and the blue to come through. Rhodamine also absorbs the green and the yellow sectors of the spectrum. The exclusion of the green sector by these filters results in their

appearing opaque when held up against the night-sky, neither the individual stars—except those which are very highly luminous—nor the background illumination being visible through them.

Several dye-stuffs can be used to prepare colour filters which appear green in colour by transmitted light in day-time. Spectroscopic examination shows this colour to be the result of a nearly complete absorption of the yellow and red sectors of the spectrum, while the blue sector is also much weakened and the green sector comes through freely. As examples of such filters may be mentioned those prepared with the dye-stuffs “fast-green”, “brilliant green” and “lissamine green”. As is to be expected, filters of this description transmit the light of the night-sky very freely, both the background illumination and the feeblest stars being seen clearly through them.

Filters exhibiting diverse colours by transmitted light in day-time may exhibit a partial absorption of the green sector of the spectrum. As examples, we may mention filters which appear of an orange hue in daylight. Such filters exhibit an extinction of the blue as also of the green up to about $545\text{ m}\mu$ and a practically free transmission of greater wavelengths. When viewed through such a filter, the night-sky exhibits a weakening both of the general luminosity and of the brightness of the individual stars. But they continue to be visible. Filters which appear of a blue colour by daylight but are only partially transparent to the green of the spectrum exhibit a similar behaviour when the night-sky is viewed through them.

The spectra of individual stars: An observer with a replica diffraction grating held before his eye and viewing the sky on a clear moonless night will notice that the stars of exceptionally high luminosity, e.g., Sirius, α -Centauri, Arcturus, Vega, Capella and Rigel are accompanied by brilliantly-coloured streaks of light which are their diffraction spectra of the first and higher orders. Less brilliant stars also exhibit a similar phenomenon but with much diminished intensity. Indeed, in such cases, only the spectra of the first order can be seen and the colours are barely perceptible. The spectra also appear much shortened, the blue and red terminations being hardly noticeable. Fainter stars do not show the phenomenon at all, for the reason that the general luminous background of sky-illumination overpowers the faint diffraction spectra.

It is obviously a matter of interest to ascertain how the spectra of the less luminous stars present themselves to the unaided vision. The observations with colour filters described above demonstrate that the spectral region which is effective in our perceiving most of the stars in the sky is limited to the wavelength range between 500 and $560\text{ m}\mu$. To observe their spectra directly, it is necessary to exclude the general luminosity of the sky. This requirement may be met by viewing the night-sky through a long narrow slit, the observer and his diffraction grating being located inside a completely darkened room. The spectra of the individual stars are then seen as bright streaks crossing the elongated spectrum of

the diffuse general illumination of the sky. Except in the case of the highly luminous stars, the streaks do not extend outside the spectrum of the diffuse illumination.

The question naturally arises whether the spectrum of the so-called "diffuse illumination" of the sky is itself not the result of the superposition of a great number of streaks representing the spectra of the individual stars. Any attempt to answer this question by observational study should evidently be made in specially favourable circumstances, viz., in an observatory situated at a high level and not troubled with the illumination of the sky by the light of neighbouring cities.

The new physiology of vision—Chapter XXXVIII. The adaptation of vision to dim light

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The enormous disparity between the illumination available from natural sources by day and by night justifies the terms day-vision and night-vision being used to describe the functioning of our visual organs respectively in these two widely different sets of circumstances. From the investigations set out in the two preceding chapters, it emerged that there is no real difference between day-vision and night-vision except that in the latter case, the red, yellow and blue sectors of the spectrum are not perceived and that only the green, in other words, the part of the spectrum appearing in the wavelength range between 500 and 560 $m\mu$ is effective and enables us to perceive illuminated objects. With the aid of three colour-filters, viz., those which transmit only the red, green and blue sectors respectively—excluding in each case the rest of the spectrum—these features of night-vision can be readily demonstrated. The red and the blue filters appear opaque and do not allow of feebly illuminated objects being readily perceived through them. On the other hand, the green filter appears transparent and allows the details of the objects under view to be seen and recognised.

The change-over from day-vision to night-vision can be followed by an observer who views a long narrow slit through which the light of the sky finds entry into a darkened room, while holding a replica diffraction-grating before his eye. The insertion of each colour-filter in turn before the diffraction-grating allows the particular part of the spectrum which it transmits to be seen while the rest is excluded. If such observations are made during the twilight period with the red or the blue filters, a progressive contraction followed by a total extinction is noticeable of the parts of the spectrum which they respectively transmit. But in the case of the green filter, the part of the spectrum transmitted by it remains visible and continues to be seen even after the cessation of twilight and when the light under observation is that of the night-sky.

The differences between day-vision and night-vision can also be demonstrated by observations in a dark room entry of daylight into which is permitted, under control by an iris-diaphragm covering a circular sky-light. The opening of the iris can be set as desired, thereby enabling the illumination of objects within the room to be varied over a great range. Holding a colour filter before his eye, the observer

can view the objects in the room at any desired level of illumination. Particularly suitable for such observations is an ophthalmic chart, viz., a white card carrying several rows of printed letters of different sizes. When the opening of the iris is large enough, the chart can be seen and the letters on it can be read through each of the three colour-filters in turn, viz., red, green and blue. But when the iris is closed down sufficiently, the chart ceases to be visible through the red and the blue filters, whereas it can be seen and the printed letters on it can be read using the green filter.

During the period of twilight which intervenes between day and night, human vision adjusts itself automatically to the greatly reduced level of illumination which results from the setting of the sun. If, however, the transition from light to darkness is sudden as for example when an observer moves into a dimly-lighted room from a brightly-lighted exterior, he is at first unable to perceive the faintly illuminated objects inside the room. It is found that an appreciable interval of time is needed for his vision to adjust itself to the lower level of illumination. This change or adjustment of vision to an altered level of illumination is usually referred to as "adaptation". It has been the topic of numerous studies and discussions. We shall in what follows consider the subject in the light of our findings regarding the nature of the differences between day-vision and night-vision. We shall also report some new observational results which enable us to arrive at definite conclusions regarding the nature and origin of the phenomenon.

The period of adaptation: The basic feature of adaptation is that it is progressive with time. It begins when the observer whose vision has fully adjusted itself to a particular level of illumination of the objects around him transfers himself to a different environment which we shall assume, represents a lower level of brightness. The adaptation ends when his vision attains a steady state corresponding to such lower level. The questions which arise and call for our answer are the following. What is the nature of the change which occurs in the visual apparatus and what determines the time required for it?

When considering these questions, we may usefully here recall some well-known facts of experience. The time required for vision to adapt itself to a new set of circumstances is determined both by its initial and final states. It can be stated in a general way that the more widely different they are, the greater is the time needed. If, for example, the first level is in the range of day-light vision and the second in the range of night-vision, the time needed would be quite considerable. If, on the other hand, both of the levels of brightness are in the day-light range, the adaptation would take place much more quickly.

It may also be remarked that the role played by adaptation in the perception of light is specially conspicuous in the case of faintly illuminated objects but is much less evident in the case of those which are brilliantly lighted. For example, an observer entering a dimly-lit room may find some difficulty in recognising objects located in the darker corners. But any metallic objects or other polished surfaces

in the same area which reflect light falling on them directly towards his eyes are immediately perceived.

To obtain a fuller insight into the nature and origin of the phenomena of adaptation, we may use the same technique as that described earlier. The observations are conveniently made in a dark room of which the illumination admits of being controlled by opening or closing an iris-diaphragm covering a circular sky-light. The use of an ophthalmic chart as the test-object is also highly advantageous. The observer should place himself at such a distance from the chart that he can read all the letters on it without difficulty if the illumination is adequate. To begin with, the observer's vision may be adapted to bright day-light and the iris-opening of the sky-light reduced to its minimum, so that the illumination of the chart is extremely feeble. The process of accommodation is then naturally slow. The observations may then be repeated in successive stages with the iris more widely open and the shortening of the period of accommodation which results thereby is made evident.

Studies of adaptation in this manner reveal that the progressive increase of the observed brightness of the test-chart during the period of adaptation is accompanied by a simultaneous increase in the visibility of the printed letters on the test-chart. Another remarkable phenomenon is also noticed in these studies. If at any stage during the progress of adaptation, the observer moves forward and comes close to the chart, he notices a great brightening up of its entire area, while simultaneously all the letters on it spring into view and can be read with ease. A similar spectacular increase of visual brightness is exhibited by any feebly illuminated diffusing screen when an observer approaches close to it when his vision is not fully adapted to the low level of brightness.

Another significant observation of interest may also be noted here. Two similar diffusing screens of white plastic material are placed in the path of the light diverging from the sky-light but at different distances from it. For example, one may be twice as far from the light-source as the other. The ratio of their illuminations is then one to four, but their visually observed brightness differs to a far greater extent. At the beginning of the period of adaptation the more distant screen is scarcely visible, while the nearer screen is a conspicuous object. Only at a later stage does the ratio of their visually observed brightness become at all comparable with the ratio of the illumination of two screens.

The nature of adaptation: The observations set forth above leave little room for doubt as to the exact nature of the changes in the visual apparatus that manifest themselves in the phenomena of adaptation. What is actually observed is that when an observer remains for a sufficient period in a brightly lighted environment, there is a large reduction in his power to perceive feeble light, but that on the other hand the ability to perceive bright light remains more or less unimpaired. The only explanation of this phenomenon that could be suggested and that could be reconciled with the facts of observation set forth above is that the individual

receptors of light in the retina exhibit an effect in the nature of fatigue as the result of a continued functioning in bright light for a long period of time. Such fatigue results in their inability to receive and transmit very weak impulses to the cerebral centres, while on the other hand their ability to receive and transmit more powerful impulses is not seriously impaired. Prolonged rest in darkness may be expected to abolish this fatigue and enable feeble illumination to be perceived to the same extent and in the same manner as bright light.

The new physiology of vision—Chapter XXXIX. Daltonian colour vision

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The following questions arise regarding the abnormal colour perceptions exhibited by certain individuals. What exactly are the colours which they perceive and in what other respects do their visual perceptions differ from those of normal individuals? Further, what is the origin of these differences: in other words, what is the difference in the nature of the visual processes which is responsible for these abnormalities? Colour, though determined by the physical nature of the light which is perceived, is nevertheless a subjective phenomenon. This circumstance may make it difficult to ascertain what the actual facts are in any particular case. Complications would also arise, if the cases of defective colour vision met with are not all of the same kind, as is generally believed.

In earlier chapters, the subject of defective colour vision has been considered and it has already been shown that normal and abnormal colour vision can be brought into an intelligible relationship with each other. A few cases have also been considered in detail and it has been shown that they support the correctness of the approach made to the subject. Nevertheless, it was evident that further studies were necessary to obtain a fuller and deeper understanding of the facts observed. Hopes of further advance lay in the direction of applying new methods of investigation to the study of abnormal colour vision and of relating the results to those already established in the case of normal vision. While it was evidently desirable to extend the study to more cases, it was clear from the outset that it would be particularly useful to work with selected individuals exhibiting abnormal colour vision who by reason of their scientific training and experience could be relied upon to render trustworthy reports of their own personal observations in the contemplated studies.

In the present chapter, we shall set out the results which have emerged from an intensive study of abnormal colour vision made with the aid of an individual who will be referred to in what follows as Dhruva, which, of course, is not his real name. Dhruva is a highly qualified physicist. That his colour vision was abnormal was discovered in the course of surveys undertaken by the author to find such cases. His scientific competence and his enthusiastic co-operation in the investigation has made a real advance possible in our knowledge and understanding of the subject of abnormal colour vision and of its relationship to normal vision.

The colour sequence in the spectrum: It is a remarkable fact that a person endowed with normal vision is capable of recognising quite small differences in colour if these are presented to him in an appropriate fashion. For example, the two yellow lines in the spectrum of a mercury lamp whose wavelengths are respectively 5770 and 5790 Å and which are of equal intensity when seen simultaneously through the eye-piece of a spectrometer exhibit an observable difference in colour, the former line appearing of a greenish hue while the latter is a pure yellow. This fact suggested to the author that an arrangement by which the entire continuous spectrum is presented as a series of discrete lines but without any change in the relative intensities of its different parts would be a useful device for the study of the spectrum colours and especially for exhibiting the differences in the rate of progression of colour in different parts of the spectrum.

The idea indicated above can be realised in practice by setting two half-silvered plates of glass in parallel positions before the slit of a wavelength spectrometer and viewing the spectrum of a brilliant source of white light of restricted area normally through the combination. The entire spectrum is then seen as an array of discrete lines or bands in a dark field, their number and spacing being determined by the separation between the plates. By making one of the plates movable with respect to the other, the number of lines or bands seen in the spectrum can be varied within wide limits. The more numerous they are, the smaller would be the difference in wavelengths between adjacent ones. If such difference is large enough, they would exhibit an observable difference in colour. But this would not be the case, if the bands are numerous and therefore closely spaced. Much would depend on the particular part of the spectrum and the rate at which the progression of colour is manifested therein.

A channelled spectrum with approximately 100 bands in it produced in the manner explained was presented to Dhruva. He examined it through the eye-piece of a wavelength spectrometer and listed the parts of the spectrum which appeared to him to be different in colour and their respective wavelength limits. His findings are exhibited on the right-hand side of figure 1, while those of an observer with normal colour vision made under exactly the same conditions are shown on the left-hand side of the figure.

A comparative study of the two sides of figure 1 is very instructive. To a normal observer, the yellow of the spectrum appears as a narrow strip in the wavelength range from 575 to 585 mμ. But, to Dhruva under the particular conditions of observation, it appears as a wide tract of the spectrum and the regions in which a normal observer perceives the colours of red and green have for the most part also been replaced by colours related to or resembling yellow. It is clear from the diagram that Dhruva's vision is daltonian. It would nevertheless not be correct to say that he is either red-blind or green-blind or both red-blind and green-blind. A correct description of what is actually observed is that the sensation of yellow perceived by him has extended itself so as to cover a large part of the spectrum and modify the colours seen by a normal observer in adjoining areas. In this

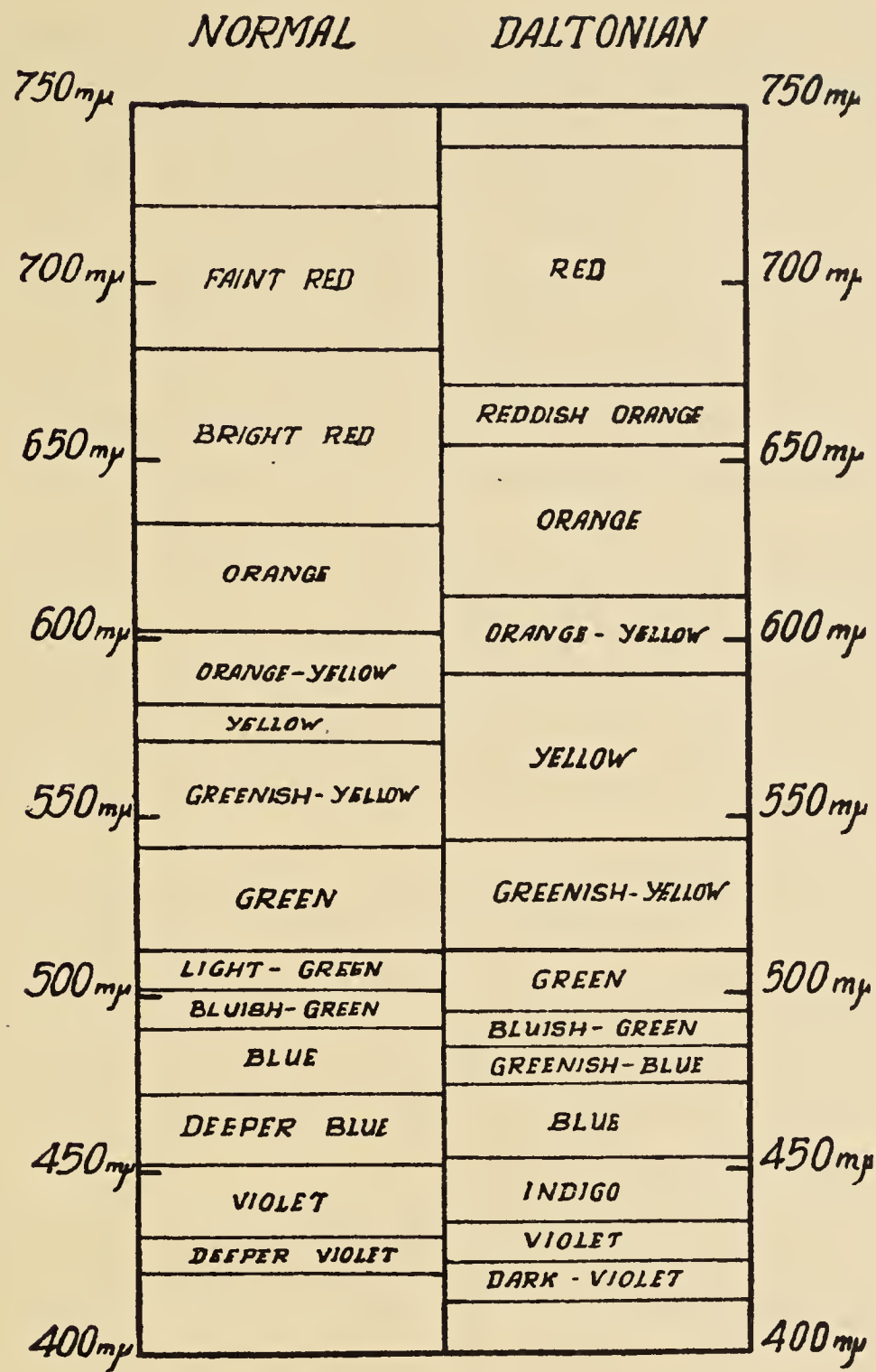


Figure 1. Colour sequence in the spectrum.

context, it is noteworthy that to Dhruva, the part of the spectrum which appeared to be the most luminous is that in which a normal observer locates the yellow strip.

Effect of luminosity on the spectrum colours: A remarkable and convincing demonstration that daltonian vision arises by reason of an abnormal enhancement of the sensation of yellow in relation to other colours in the spectrum is forthcoming from the observations of Dhruva on the emission spectrum of a heated tungsten filament over a wide range of temperatures. The filament is a straight long coil of fine wire and is heated by the passage of an electric current through it. This current could be controlled by a rheostat, and the temperature of

the filament could therefore be stepped up over a great range, beginning with its emission barely visible as a dull red glow and going up to one at which the filament emits a brilliant white light. The spectrum of the emission can be examined very simply by viewing the luminous filament from an appropriate distance through a replica diffraction grating held in front of the observer's eye. As the temperature is raised a whole series of changes manifests itself in the colours visible in the diffraction spectrum of the first order. The observations are made in a completely darkened room, a dark background being provided so that the spectrum could be viewed against it. The observations of Dhruva are reproduced below exactly as recorded by him at the time.

- (1) *Extremely low levels*: At these faint and barely perceptible levels, only the green portion of the spectrum is visible.
- (2) At slightly higher levels, the red region faintly makes its appearance, though the green is brighter. The relative lengths of the regions are green (1); red (0.5).
- (3) At still higher levels, the intensity maximum shifts to the red region, and at the stage when the maximum is definitely at the red, the relative lengths are green (1); red (1).
- (4) The next stage is reached when the yellow distinctly appears. Simultaneously the maximum intensity region moves over to orange-yellow. The blue also makes its appearance about this stage. Relative lengths are: blue (1); green (1.5); yellow (1); red *plus* orange (1.5).
- (5) At higher luminosity, the yellow invades the red and assumes the position of maximum luminosity. At this stage, the relative lengths are: blue (1.5); green (1); yellow (2); red *plus* orange (2).
- (6) This trend is continued at higher levels, the yellow becoming most intense and invading the red and the green. The relative lengths of the colour regions at this brightest stage are: blue (2); green (0.5); yellow (4); red (1).

An observer with normal colour vision observing the spectrum of the glowing tungsten filament under exactly the same conditions as in the observations by Dhruva also notices changes in the character of the spectrum of the emitted light, including especially the manifestation and progressive increase in luminosity of the yellow sector. But there is a great difference between Dhruva's observations and those of the normal individual. The development of the yellow sector, and its invasion of the green and red sectors are far more striking in daltonian vision than for a normal observer. The normal observer does not observe the contraction of the green and red sectors conspicuously evident in daltonian vision.

The yellow of the spectrum is the major visual sensation to an observer with normal colour vision at ordinary or daylight levels of illumination. It is totally absent in night-vision; *per contra*, at extremely high levels of brightness, as has been described in an earlier chapter, the yellow sensation becomes the dominant sensation to an extraordinary extent, reducing the rest of the spectrum to a relatively insignificant position. In other words, the characteristics of daltonian

vision resemble those exhibited by normal colour vision at exceptionally high luminous intensities. The abnormality which is responsible for their manifestation is thus connected with the visual mechanism which determines the strength of the yellow sensation at various levels of brightness.

The perception of red: It will be noticed from figure 1 that the part of the spectrum described as red by Dhruva is of very low luminosity to a normal observer, while the part which is bright red to a normal observer appears as orange to Dhruva. It follows that while it would be entirely incorrect to describe Dhruva as red-blind, nevertheless his perceptions of red would be much weaker than those of normal individuals. This is borne out by the studies made of the characteristics of his vision. When the colour test-charts published by the American Optical Society were shown to him, he was unable to recognise the numeral 9 very clearly exhibited as a sequence of spots of a red colour surrounded by other spots of similar shapes of which some were grey and the others black. Likewise, in these charts, he was unable to recognise numerals printed as dots in various shades and depths of a red hue in a field surrounded by dots printed in various shades and depths of green and greenish-yellow. He was also unable to recognise numerals printed in dots of pale red colour in a field of dots exhibiting various shades of pale yellow and brown.

The colour vision of Dhruva was also tested by showing numerous hard-cover books which he had not seen previously and asking him to name their colours. Amongst them were several exhibiting hues ranging from a brilliant red to a dark brown tinged with red. In several cases, he named as red, books of which the cover was more nearly brown than red. From these and other instances, it was evident that his perceptions of red differed rather widely from those of normal individuals. Similar differences become evident when he was presented with a set of samples of dyed silk fabrics and asked to classify them and to name their colours.

Perception of green: It is evident from figure 1 that the sharp distinction between green and yellow manifested in the colour vision of normal individuals does not exist for Dhruva. Indeed, the yellow lines at $579\text{ m}\mu$ and the green line at $546\text{ m}\mu$ of the mercury lamp did not appear to him to be distinguishable in colour. Figure 1 indicates that Dhruva perceives as green in colour a part of the spectrum adjoining the blue at about $500\text{ m}\mu$. Presumably therefore in certain cases, he should be capable of recognising as different from each other in colour the objects which are named respectively as green, yellow and red by normal observers.

Presented with several books bound in hard-covers of various colours, Dhruva in most cases named as green or dark green the books which would be described in the same manner by normal observers. There were however a few cases in which his naming of colours differed quite sharply from the usual ones. A book with an orange-yellow cover was named as green, and another as ash-grey which

was a light greenish-blue. A third book which was a pale yellow was named as a greenish-yellow. In his naming of the colours of a series of dyed silks, it was evident that Dhruva found it difficult to distinguish pure greens from bluish greens and likewise to distinguish blues from bluish-green colours.

In the tests made with the colour charts of the American Optical Company, Dhruva read without error or hesitation the numerals in the charts in which they were printed as dots in greenish colours surrounded by a field of dots printed in colours ranging from yellow to orange. Likewise, he could read without error or hesitation numerals printed as dots ranging in colour from pale yellow to orange surrounded by a field of dots printed in colours of various shades of green.

The purple sensation: The studies of composite colours described in earlier chapters made it evident that a purple sensation results when the yellow sector is eliminated from the spectrum of white light while the blue, green and red sectors are left without change. Any alteration in the relative strength of the red sector as compared with the strength of the blue and green sector taken together results in different shades of purple. The weakening of the red sector results in the purple assuming bluer shades, while any weakening of the blue or green sectors results in the purple exhibiting hues more nearly akin to red.

In view of the foregoing remarks, it is significant that when Dhruva was shown the flowers of the ground orchid "*Spathoglottis plicata*" he named their colour as blue, whereas to a normal observer they exhibit a reddish purple colour. Spectroscopic examination reveals three well defined absorption bands in the light transmitted through or reflected by the petals of the flower. The principal band extinguishes the yellow sector, while the two other weaker bands appear respectively in the green and in the greenish-blue, thus accounting for the reddish-purple colour of the flower. That Dhruva perceives the flowers as blue in colour is a demonstration that his perception of red is very weak.

Bougainvillia with its clusters of brilliantly-coloured bracts is one of the best-known and most highly favoured of ornamental plants. Several varieties of it are known with bracts exhibiting purple hues. Bracts of three such varieties were shown to Dhruva. He named all of them as blue flowers, qualified by the remark in brackets (tinge of violet) in the case of the deepest purple, and (light) in the case of the palest purple.

The colours of interference: Dhruva was shown three items of apparatus exhibiting interference colours brilliantly on a large scale. The following is a description in his own words of the region surrounding the central dark spots in the pattern exhibiting Newton's Rings: First ring—Reddish inside grading over to darkness; this is followed by a brighter region where the colours change radially blue to yellow before the next dark ring is reached. There is a further bright zone where the colours change from blue to yellow; the next dark ring is fainter, i.e., contrast is less. As we move across radially, further rings appear, but it occurs to me as if the

bluish tinge is less and less and the contrast drops very sharply—rings beyond the fifth or sixth being barely visible. Up to the fourth ring, the yellow looks prominent in the bright region, beyond which it is a uniform grey (except for alternation of intensities due to the rings).

Interference fringes of wedge-shaped film: These are described by Dhruva as follows: Starting from the top of the plate, the first dark band is bordered by red and orange at the top and blue at the bottom. This is followed (proceeding downwards) by orange, black (i.e., the dark band) and blue for the second band. The third band is bordered by orange red at the top but the blue is much fainter. Three more bands are visible, but with decreasing contrast. The colour variations for these are not visible—they can only be described as shades of grey.

The interference fringes in a pattern of ovals: The outermost dark oval ring is followed by patches of blue and orange red, to the second (inner) dark ring. The transition to the third ring is similar, but the bluish tinge is much weaker here. The fourth and innermost ring is much fainter in contrast and appears as a dull brownish-red. The patch inside this ring has the same contour, and shows up as a dull grey contrast to the background.

The new physiology of vision—Chapter XL. The colours of iolite

SIR C V RAMAN

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An attractive display of colour by a mineral serves to gain for it a position of esteem as a gemstone. The colour is determined, in the first place, by the absorption of light in its passage through the solid. But this is only one aspect of the matter. Scarcely less important is the role played by the physiology of vision. For, the perceived colour of a gemstone results from the synthesis by the visual mechanism of the different spectral components of the light emerging from its interior. This field of investigation was traversed in an earlier chapter, but we return to it to consider the particularly interesting case of iolite.

The name iolite is derived from the Greek word for violet and is indicative of the colour of the gemstone. It is found in gem-gravels as water-worn pebbles, one of the principal sources being Ceylon. Iolite is also known by another name as cordierite, a mineral which is found associated with gneisses and schists and exhibits the phenomenon of pleochroism in a very striking fashion. It is with cordierite that Sir David Brewster discovered the optical effect known as “Brewster’s brushes” which we shall refer to later in this paper and which stands in close relationship to the colour and pleochroism of biaxial crystals.

Cordierite is found in various parts of South India and especially in the Coimbatore district. Its optical properties were made the subject of a penetrating study by Dr S Pancharatnam and the memoirs describing his results were illustrated by a striking and beautiful series of photographs. These will be found in the *Proceedings of the Indian Academy of Sciences*, Vol. 42, 1955, as plates V, VI and VII and in Vol. 40, 1957, as plates I and II. We shall have occasion later to refer to Dr Pancharatnam’s publications.

The pleochroism of iolite: Though much of the material from Coimbatore is in the form of irregular lumps, some specimens are available which were evidently the result of the cleavages or partings of crystalline blocks. These specimens were ground to the form of plates and then polished, thereby enabling the colour and other optical characters of the crystal to be critically examined. The plates, each a few mm thick, prepared in this manner, fell into two distinct groups. The first group shows a brownish-yellow colour by transmitted light. Viewed through a

polaroid, this light is found to be completely polarised; it comes through freely in one setting of the polaroid and is extinguished in a perpendicular setting. Viewed edgewise, plates of this group allow light of a brownish-yellow colour to filter through in one direction, but are perfectly opaque in a perpendicular direction.

The second group of plates shows a wholly different behaviour. The light transmitted by them exhibits a blue colour, the thicker specimens showing a deeper colour as is to be expected. Viewed normally through a polaroid, the plates of this group show a noticeable variation in the colour and intensity of the transmitted light as the polaroid is rotated. The transmitted light appears brighter and less saturated in colour in one setting of the polaroid and less bright and of a deeper blue in a perpendicular setting. The edges of one such plate were smoothed and polished, so that it could be held edgewise and its optical behaviour examined. Despite the rather long path which the light has then to traverse, it comes through freely and allows distant objects to be seen quite distinctly. The colour of the light thus perceived is reddish-brown. Examination through a polaroid shows it to be completely polarised.

Observations have also been made with a small piece which was cut and polished to the shape of an approximately cubical block of about 4 mm edge-length. The light transmitted by the block in the three mutually perpendicular directions showed three different colours. One was a very pale yellow, the second a deep blue and the third a light blue. The pale yellow light emerging through one pair of faces when viewed through a polaroid is found to be completely extinguished in one setting of the polaroid, and comes through freely in the perpendicular setting. The light of a deep blue colour coming through the second pair of faces was found to be much weakened but not totally extinguished in a particular setting of the polaroid, but comes through with little noticeable change in the perpendicular setting. The light of a pale blue colour coming through the third pair of faces behaves differently. It is not extinguished in any setting of the polaroid but shows alternations of colour and intensity as the polaroid was turned round, exhibiting a pale yellow colour in one setting and a pale blue colour in the perpendicular setting.

A polished sphere of iolite 6 mm in diameter has also been used to exhibit the pleochroism of the gemstone. Held between the finger-tips, a distant window may be viewed through it. Both the colour and the luminosity of the image as seen through the sphere alter as this is rolled between the finger-tips. The changes depend on the way the sphere is held, in other words, on the axis of its rotation. In certain cases, the image seen is brilliant and its colour a pale yellow and then alters quickly to a deep blue of low luminosity. In other cases, the changes in colour and luminosity are less rapid and less striking.

Brewster's brushes: The specimen of iolite with which Dr Pancharatnam obtained his photographs was specially prepared in the form of a polished plate about 2 mm thick and having its faces normal to one of the two optic axes of the

crystal. Held at arm's length and viewed against the bright sky, the appearance of the plate changes in a remarkable way as the angle which it makes with the line of vision is altered. When held in a particular position and tilted about a vertical axis in either direction, it exhibits a beautiful blue colour. Held in the same position but tilted about a horizontal axis, it appears bright and of a pale yellow colour in one setting and much less bright and a pale bluish-grey in another setting.

The origin of the effects described above becomes evident when the plate is held close to the observer's eye and the bright sky is viewed through it. Brewster's brushes then appear in the field of view and are seen extending outwards on either side of a narrow gap which covers the region of the optic axis. The brushes are for the most part of a brilliant blue colour. But the areas above and below the brushes have a quite different appearance. They also differ from each other in colour and luminosity, one side being dimmer and of a pale blue colour, and the other side much brighter and a pale yellow. That the colour and configuration of Brewster's brushes are closely related to the pleochroism of the crystal is thereby made evident.

To observe Brewster's brushes, it is not essential that the specimen should be cut normal to an optical axis. Indeed, the plates prepared from the available material which present a blue colour when held normally, exhibit Brewster's brushes when held obliquely and the bright sky is viewed through them in an appropriate direction. The thicker the specimen, the more striking are the brushes which are visible. It should be mentioned here that the colours of the brushes are noticeably influenced by the dispersion of the optic axes of the crystal. The blue brushes are seen to be edged with a purplish-red on one side. This effect is particularly conspicuous when the plates are held very obliquely.

The absorption spectrum of iolite: Dr Pancharatnam used the light of a sodium lamp for photographing the various phenomena observed and discussed by him. The monochromatism of this light serves to bring out the interference effects with maximum clarity. But it has also to be noted that the coincidence of the wavelength of the light employed with the region of the spectrum in which the absorption of iolite is particularly strong played an important role and helped to make the photographs as striking as they actually are. That this circumstance is also responsible for the magnificent blue colour which iolite exhibits in certain orientations can be readily demonstrated with the specimen used by Dr Pancharatnam in his work. Holding the plate against the bright sky, the spectrum of the transmitted light is examined through a direct-vision spectroscopy. By tilting the plate to one or another of the four positions described earlier, the spectral constitution of the transmitted light in each case and its relation to the observed colour can be conveniently studied. That the practically complete extinction of the yellow sector in the spectrum goes hand in hand with the production of the deep blue colour of Brewster's brushes then becomes evident.

It should be remembered that we are concerned not only with the colour of the transmitted light in the various cases but also with the attendant changes in the brightness which are indeed considerable. The extinction of the blue sector alone would result in the colour changing to yellow, but the luminosity would not be greatly diminished. On the other hand, any weakening of the red, yellow and green sectors while the blue sector is freely transmitted would result in a large reduction of the brightness of the transmitted light, besides a change in its colour. In each case, this is what is actually observed.

The new physiology of vision—Chapter XLI. Photography in colour

SIR C V RAMAN

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Pictorial photography is made immensely more interesting by the additional feature of colour, thereby making the record resemble more nearly what we observe with our eyes. It is not surprising, therefore, that photography in colour has attained great popularity and that it has received attention from numerous industrial corporations who have sought to provide the means for making it possible, viz., special cameras, photographic films and plates, methods of copying and multiplying the pictures taken, and finally also, projection apparatus for viewing films in colour as transparencies. Numerous techniques have been evolved for obtaining pictures in colour, and several of them have achieved a considerable measure of success and have accordingly been received into popular favour. It is not possible, nor is it proposed here to list these processes or to describe any of them in howsoever cursory a manner. What we are concerned with here is the role played by the characteristics of human vision in colour photography and the extent to which photography in colour can or does succeed in reproducing the appearance of objects as seen with our eyes.

It is evident that the two issues stated above are closely interrelated. For colour photography to be even reasonably successful, it has to take account of and be based upon the characteristics of human vision in respect of the sensations of colour. These characteristics fall into two broad divisions, viz., the sensations excited by the monochromatic radiation appearing in different parts of the spectrum, and the sensations excited by spectrally composite radiation. In most cases, we are concerned with composite radiation, the perceived colour of which is determined by the visual synthesis of the different spectral components of the light which is perceived. These remarks apply equally to the colours of the objects photographed and to their colours as exhibited in a photographic picture. The subject of the visual synthesis of colour thus plays an extremely important role in the field of colour photography.

Colour has such a powerful aesthetic and emotional appeal that a picture or a painting which makes no claim to be a faithful colour-rendering of the object depicted may nevertheless be admired and even highly valued. Fidelity in the reproduction of colour by photography may to some extent therefore be regarded

as being only of academic interest. But this is by no means always the case, especially when colour photography is made use of to convey to a possible purchaser as exact a picture as possible of the article which he desires to obtain. Reproductions of celebrated works of art, of coloured textiles, of ceramic wares and different varieties of favourite flowers may be cited as examples of this situation.

A critical examination of the success or failure of colour photography, in other words, a determination of the measure of success actually achieved by any given process in reproducing colour and of the reasons for its failures, if any, evidently demands a proper choice of the test-objects made use of in the study. It is necessary that the object should display a wide range of colours, and that the spectral composition of the light which emerges from each point of the object should be precisely known and is precisely reproducible. Such a test-object is provided by the colours of interference, produced either in the Newtonian fashion between two polished surfaces of glass having different radii of curvature or between two flat plates of glass very slightly inclined to each other or in some other way. In earlier chapters the results which emerge from the study of such patterns in various other contexts have already been set out and described, viz., studies of the visual synthesis of colour and studies of defective colour-vision. From these instances, it is evident that the photography of interference patterns in colour would enable us to determine whether the processed colour-films do exhibit the same features as those visually observed in the patterns themselves, and if not, why not.

We begin with interference patterns of the Newtonian type. As usually produced and observed between two spherical surfaces of large radii of curvature, the rings are rather closely spaced and can be properly seen only through a magnifier. Much better suited for our present purpose are the rings produced on a much larger scale between two flat thick plates of glass of the kind ordinarily used for glazing large windows. The processes used in manufacturing such glass plates result in extensive areas appearing as cylindrical surfaces of very large radius. If two pieces of such glass, each about 5 cm square, are cut out and their edges are smoothed and the faces are placed in contact with their cylindrical axes in crossed positions, perfect circular interference-rings of the Newtonian type on a large scale are produced between the surfaces. These rings exhibit the colour sequence in a very striking fashion and do not need a magnifier for enabling them to be critically examined and studied.

Newtonian interference patterns produced in the manner described above have been photographed, using the white light of a tungsten-filament lamp and with colour-films bearing the well-known name of Kodak, and also with different exposures, in view of the influence which the exposure-time is known to exert on the final picture as seen in the processed film. The very striking result then emerged that the photographed colour-film of the interference pattern does not exhibit the colour-sequence in the pattern as seen directly, but differs therefrom in

a very conspicuous manner. In seeking for an explanation of these differences, a comparison was made between the features seen in the processed film, and the original patterns as viewed through a piece of neodymium glass, which, as is well known, exerts a powerful absorption in the wavelength range between 570 and 600 $m\mu$ and thereby effectively excludes the yellow sector of the spectrum, its absorption in the rest of the spectrum being relatively negligible. The interference pattern as seen in white light through the neodymium glass, and the same pattern as recorded on the colour-film without the neodymium filter showed many features in common, and could indeed be described as resembling each other closely.

The facts stated above are evidently of such high significance that it seems desirable to proceed to some further detail. The extremely important role played by the yellow sector of the spectrum in determining the features of the Newtonian interference pattern may be demonstrated in the following manner. The pattern is viewed by reflected light, one-half of it as seen with white light, and the other as seen with monochromatic yellow light, e.g., the light of a sodium lamp. The two halves appear in juxtaposition, and there is an astonishingly close coincidence between the two sets of rings. Indeed, the rings as seen with sodium light appear as continuations of the rings seen with white light, the first five minima of illumination which are conspicuously evident in the white-light pattern appearing in positions indistinguishable from the dark rings of the sodium-light pattern.

As viewed through the neodymium glass, as also in the white-light pattern as photographed on a colour-film, we observe in the first place, that the rings which are visible are far more numerous. Further, the entire field of interferences exhibits alternate regions which are totally different in their observable characters. In one region, we find vivid colours, and this is followed by another in which there is a succession of dark and bright rings with no noticeable colour and this again is followed by a region in which colours are distinctly visible. The removal of the yellow sector by the neodymium filter evidently produces these effects on the interference pattern as seen visually. That the same effects are noticeable in the pattern recorded in the colour film indicates that the photographic technique employed for recording colour takes no account of the existence of an independent and extremely powerful yellow sector in the spectrum of white light.

Essentially similar differences are also noticed between the interference pattern of a wedge-shaped air-film as observed visually with white light and as photographed in colour with a Kodak film. Likewise, the pattern visible in white light but with a neodymium glass filter interposed shows a remarkably close correspondence with the features noticed in the photographic colour film record of the white-light pattern. We draw the same inference, viz., that the photographic techniques used for the reproduction of colour fail to take into account the existence of an independent and extremely powerful yellow sector in the spectrum. In other words, they make the mistake of assuming that the yellow of

the spectrum is adequately taken care of when it is regarded as a superposition of the green and the red of the spectrum. This, of course, is one of the fundamental errors which vitiates the trichromatic theory of colour, as has already been demonstrated in other ways in earlier chapters. The extraordinarily important role that the yellow sector of the spectrum plays in the visual synthesis of colour has been illustrated in those chapters by numerous examples, viz., the colours of flowers, the colours of dyed silks, of natural and synthetic gemstones, as also structural colours of various sorts. One need not therefore be surprised that the reproduction of colour by photographic processes is, in general, only an approximation to the reality.

The new physiology of vision—Chapter XLII. Further observations with the neodymium filter

SIR C V RAMAN

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The highly important role played in human vision by the yellow sector of the spectrum emerged very clearly from the studies described in the earlier chapters. Striking demonstrations of this are furnished by the effect of the interposition before the observer's eye of a piece of glass coloured by neodymium oxide which is of just sufficient thickness to exhibit a practically complete cut-off of the spectral region between 570 and 600 m μ , while in other regions the absorption is relatively much weaker. Preliminary observations made with such a filter have already been described earlier. But it appeared desirable to carry out a more detailed study with its aid and to present the results.

Characteristics of the filter: The specimen of neodymium glass used in the present studies was of rectangular shape 3×2 cm² and had a thickness of 5 mm. When held against a white card illuminated by direct sunlight, it appears of a light purplish colour and produces a surprisingly large reduction in intensity of the light transmitted through it. This feature is even more strikingly exhibited when extremely brilliant objects are viewed through it. For example, the dome of an observatory covered over by aluminium paint when lit by direct sunlight appeared almost insupportably brilliant when viewed by the naked eye. But when the eye is protected by the neodymium filter, one can look at the dome and continue looking at it without any discomfort. It is evident from these observations that the part of the spectrum between 570 and 600 m μ makes a large contribution to the visual brightness of any object, and that this contribution becomes proportionately much larger when the luminosity of the object goes up to high levels.

Besides the intense absorption in the yellow sector of the spectrum, there are three other regions of absorption; a fairly conspicuous band with well-defined edges in the green sector between 520 and 545 m μ , a second and feebler band between 510 and 518 m μ and finally, a weak absorption in the blue sector between 470 and 490 m μ . The conspicuously bright regions in the spectrum of the transmitted light are in the greenish-yellow between 545 and 570 m μ and in the red from 600 m μ to the long-wave end of the spectrum. As a substantial part of the

yellow sector comes through the filter unabsorbed, it is not surprising that the colour exhibited by the filter in transmitted light is only a light purple. Indeed, the filter might be easily mistaken as being of a neutral tint.

The spectroscopic behaviour of the filter provides an insight into the remarkable effects observed when differently coloured objects are viewed through it. For example, the face of a person having a fair complexion as seen through the filter exhibits a startling blood-shot appearance, evidently as the result of the extinction of the yellow in the light diffused by the human skin. Likewise, when the blue sky is seen through the filter, it appears a deeper blue. Vegetation of a light greenish-yellow colour appears a deeper and darker green. In various books and brochures, one finds illustrations representing the colours in a pure spectrum as seen by the eye. The colours seen in such illustrations are, of course, not actually those of a spectrum, but only imitations thereof. Hence, when viewed through the neodymium filter, they present an altered appearance. As is to be expected, the yellows show a marked diminution in intensity, but no great change in hue. Other colours show changes both in hue and in brightness. Orange, for example, loses brightness and changes to red.

Coloured silks: In an earlier chapter, the relationship between the spectral character of the light diffused by dyed silk and the colour exhibited by the material was studied and discussed for a variety of cases. A technique even simpler than spectroscopic examination is to view the silks through colour filters of different sorts and to note the changes in brightness and hue resulting from the introduction of the filter. We are here specially interested in the effects produced by the neodymium filter. But it is instructive to compare these with the effects produced by other colour filters of commoner types, e.g., red, orange, yellow, green, greenish-blue or blue filters. Some thirty different samples of silk were available for the tests. It is convenient for examining them to place them in a row with an ordered colour sequence. This enables them to be viewed simultaneously and compared with each other.

Of the thirty samples, twenty exhibit highly saturated colours which could be arranged in a pseudo-spectral sequence ranging from dark red to a deep violet, while the ten other specimens were very lightly dyed or else exhibit special colours and could not therefore be placed in such a sequence. These two types will be dealt with separately in what follows. The filters of glass through which the dyed silks were viewed also exhibited saturated colours which formed a pseudo-spectral sequence, viz., red, orange, yellow, green, greenish-blue and blue. The appearance of the silks forming a spectral sequence of colour changed in a significant but not unexpected manner when viewed through this series of filters.

As seen through the red filter, the six silks which range in colour from red to yellow exhibit a brilliancy increasing in that order, in other words, the yellow silk appears the most brilliant. All the other fourteen silks ranging from a light green to a deep violet appear quite dull or dark as seen through the red filter.

Seen through the orange-coloured filter, the yellow silks are still the brightest, while a greenish-yellow silk shows an appreciable brilliancy. The green silks all appear rather dull and dark. The blue-green silks appear of a dull green colour, while all the blue silks appear dull and dark.

Seen through the yellow filter, there is a remarkable increase in the relative brightness of all the green and greenish-blue silks, the latter now appearing of a brilliant green colour. The blue and violet silks remain dark.

As seen through a green filter, there is a notable diminution in the brightness of all the silks ranging from red to yellow in colour. The silks ranging from green to greenish-blue now appear fairly bright, the blue-green silks appearing green in colour. But the silks of a deep blue bright colour remain dull and dark.

Seen through a bluish-green filter, all the silks ranging from red to yellow appear quite dull. The remaining fifteen silks are fairly bright, the blue-greens and blues particularly so.

Seen through a blue filter, all the silks ranging from red to a light green appear very dull or dark. The remaining silks appear fairly bright, the light blue silks being the brightest.

In considering the visual effect produced by the neodymium filter, we have, of course, to take note of the loss of about 10% in luminosity due to reflection at the two faces of the filter. The effects of the two absorption bands in the green and of the absorption in the blue have also to be considered. These absorptions diminish the contributions to luminosity made respectively by the green and the blue regions in the spectrum. Even taking account of all these features, however, the effect due to the elimination of the part of the spectrum in the wavelength range from 570 to 600 $m\mu$ is so conspicuous that it can be recognized in most cases. The change in the visible colour produced by this absorption is specially evident in the case of the scarlet, orange, orange-yellow, yellow, and light green silks. The diminution in brightness produced by it is particularly conspicuous in the case of the orange-yellow, yellow, yellowish-green and green silks.

Rose-coloured silks: Three samples of dyed silk exhibiting a rose-red colour and differing in the depth of that colour were available; one of them was a dark rose-red, the second was of a brighter hue and the third a brilliant pink. Very remarkable changes both in brightness and in hue manifested themselves when these specimens were viewed successively through the six colour filters of the series, the three samples differing notably amongst themselves. The observations show in a more spectacular fashion what spectroscopic study reveals as the origin of the rose-red or pink colours, viz., the presence of the red and blue sectors in considerable strength and a nearly complete absorption of the green and yellow sectors. Observed through the neodymium filter, the samples manifest changes both in colour and in brilliancy. But these are not of a particularly striking nature.

Metallic colours: There are many cases in which superficial colour is manifested by reason of the variation of the opacity of the material to light over the range of the visible spectrum. The colours exhibited by the polished surfaces of metals and metallic alloys may be cited as examples. The yellow colour of gold and the red colour of copper are the best known illustrations amongst the pure metals, while brass, bronze and many other examples of metallic alloys could be mentioned. In all these cases, both the lustre and the colour of the polished surfaces exhibit striking changes when viewed through the neodymium filter. Gold appears duller and of an orange-yellow hue, while copper assumes a deeper red colour than is normally the case.

The new physiology of vision—Chapter XLIII. The colours of fluorspar

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Fluorspar is outstanding amongst minerals for its varied displays of colour. Of particular interest are the nuances of colour, which vary from a very light to a deep yellow, from the palest to the darkest violet, from a very light green to a saturated greenish-blue. The colours of fluorspar and the fact that it crystallises beautifully forming cubes or octahedra either as individuals or as clusters or as interpenetrating aggregates result in making the museum specimens of the mineral very attractive objects.

The origin of the colours displayed by fluorspar is a problem of great scientific interest. It is evident that the problem does not stand by itself but is linked with other properties of the material and especially the luminescence which fluorspar displays. For, the emission of visible light as the result of irradiation by ultraviolet rays is possible only if the material is, in the first instance, capable of absorbing the incident radiation. The manifestations of colour and the luminescence are therefore connected phenomena and it is not surprising to find that the luminescence displayed by fluorspar varies enormously in brightness from specimen to specimen, and that there are also noticeable differences in the colour, in other words, of the spectral composition of the emitted radiation. It is also not surprising that these variations in the brilliancy and colour of the emission are correlated with the colour of the specimen as seen by daylight. It is worthy of note in this connection that colourless specimens of fluorspar as well as optical fluorite prepared by slow crystallisation from purified material also exhibit the blue-violet glow under an ultraviolet lamp. But such luminosity is, in general, feeble in comparison with the brilliant displays put up by some of the naturally occurring fluorspars.

The observed relationships between colour and luminescence suggest that both phenomena may have a common origin. Further, since the luminescence is exhibited also by the synthetically prepared crystals of fluorite, there are grounds for presuming that the phenomenon is a characteristic property of the material itself connected with its crystal structure, and is not due to the presence of extraneous impurities. This presumption is strengthened when we recall the fact, long known to mineralogists, that though fluorspar crystallises in the cubic

system and should therefore be optically isotropic, nevertheless plates of the substance viewed between crossed polaroids frequently display a feeble but readily observable birefringence. This manifests itself as a network of criss-crossing lines running parallel to the cubic planes of the crystal. This is a clear indication that the natural fluorspar has a lamellar structure, instead of the complete homogeneity characteristic of an ideal crystal. Miers, in his well-known treatise on mineralogy, remarks as follows: "No relation has been traced between the colour and composition of the mineral and there is no evidence that the birefringent lamellae are due to alternation of isomorphous compounds or to zones of varying composition."

The foregoing remarks are intended to provide the background for an understanding of the particular aspect of the subject with which we are concerned here, viz., the relation between the visually perceived colour of fluorspar and the spectral composition of the light which emerges from it after traversing a sufficient thickness of the material. What follows is essentially a factual report of the results of a study of the extensive collection of fluorpars which find a place in the museum of the author's research institute. This collection, acquired in the course of years, includes specimens from several different countries, including India. It received noteworthy additions when the discovery in the year 1962 of substantial fluorspar deposits at Amba Dongar in the Baroda District of Western India enabled the author to obtain numerous specimens from that area. Colourless and transparent specimens of fluorspar as well as specimens exhibiting a variety of colours are to be found in the museum.

Green fluorspar: Perhaps the most interesting exhibits in the collection are three specimens of Chinese art sculptured from green fluorspar. One of them is 6 cm in height and represents a human figure seated on a flat pedestal and holding a ball in each hand. The material is fairly clear and is of a bright green colour. The second is a larger piece about 16 cm high, which represents a mythical animal resembling a fish on the back of which is seated a human figure holding up a flag with both arms. The colour of the material is also green, but distinctly paler than the first specimen. The third work is a massive specimen about 25 cm × 25 cm × 15 cm in its dimensions. It represents a pastoral scene and is covered with elaborate carvings which need not here be described in detail. The colour of the specimen is mostly a bright green, but there are also some parts which are of a paler hue and some parts which are distinctly bluish in colour.

Examination of the first specimen which transmits light of a bright green colour shows that this colour has its origin in the practically complete extinction of the yellow region in the spectrum in the wavelength range from 570 to 590 mμ while the green from 500 to 560 mμ remains in practically full strength. The blue sector of the spectrum is much weakened but is not totally extinguished. On the other hand, the red sector from 600 mμ to the end of the spectrum, though in diminished intensity, continues to be conspicuously visible.

The foregoing statement describes in the main what is noticeable also with the numerous other specimens in the collection exhibiting a green colour. The only qualification necessary is that the extinction of the yellow sector of the spectrum becomes less complete when the green colour exhibited by the fluorspar is less saturated. We may mention, as an example, a crystal of octahedral form in the collection which exhibits a pale green hue. The spectrum of the light which has traversed the crystal through a pair of opposing faces and an absorption path of 4 cm shows the weakening of the yellow sector in a striking fashion, but it is by no means in the nature of a complete extinction. The blue sector is also reduced in its intensity but continues to be visible, while the green and red-sectors both remain conspicuous, the former being definitely the brighter of the two.

The purple octahedron: A crystal of octahedral form with an edge-length of 1.5 cm and with lustrous faces is one of the items of special interest in the collection. Seen by transmitted light, it resembles amethystine quartz, though the colour is not very deep. The spectrum of the light transmitted through a pair of opposing faces showed the blue, green and red sectors with the same brightness relatively to each other as normally, but the regions between 560 and 600 m μ which is the yellow sector is much weakened so much so that the presence of this colour in the spectrum is scarcely recognisable.

Two massive pieces of almost colourless fluorspar in the collection exhibit large areas in which the light which has filtered through exhibits a purplish hue. In both cases, the spectroscope reveals that in this area, there is a weakening or nearly complete extinction of the yellow sector, while the other regions of the spectrum retain their normal relative intensities.

The blue octahedron: Another interesting item in the collection is a perfect octahedron of edge-length 1.5 cm which is quite clear and transparent and has lustrous faces, and which when placed on a white sheet of paper appears of a sky-blue colour. Spectroscopic examination shows that the light which has traversed the crystal through a pair of opposing faces shows an extinction of the yellow sector, while a distinct weakening of the red sector relatively to the green and the blue sectors is also noticeable.

The yellow octahedron: This crystal which is octahedral in form with an edge-length of 2 cm has lustrous faces but exhibits internal defects which prevents a free transmission between its opposing faces. It is definitely yellow in colour. The light which filters through it when examined spectroscopically shows a practically complete extinction of the blue sector, and remarkably enough also of the yellow sector in the spectrum, while the green and red sectors come through freely. Thus, we infer that the yellow colour exhibited by the crystal is a "synthetic yellow" resulting from a superposition of the red and green parts of the spectrum passing through it.

Fluorspar of optical quality: Included in the collection are two specimens which are extremely clear, in other words, free from all observable cloudiness within the volume of the crystal. One of the pieces is pyramidal in shape, 10 cm long and 7 cm broad at the base, allowing a clear optical path through it of that length. The other piece is smaller, but permits of light passing through it freely in two directions, the path lengths being 4 cm and 3 cm respectively. The interesting feature in both cases is that the transmitted light along these optical paths is of a very pale yellow colour. The spectroscope reveals that this is due to an extinction of the violet end of the spectrum beyond $430\text{ m}\mu$ and a distinct weakening upto $460\text{ m}\mu$. At greater wavelengths, there is perfect transparency.

Some remarks concerning luminescence: We may usefully here record some notes regarding the behaviour under the ultraviolet lamp of the various individual specimens referred to above.

The three Chinese works of art of green fluorspar all showed a blue-violet glow of considerable intensity. The octahedron of a pale green hue showed a violet-coloured luminescence of much smaller intensity.

The purple and blue octahedra both exhibit a feeble luminescence of a violet colour as also the massive specimens which allow light of a purplish light to filter through.

The two very clear pieces of fluorspar also exhibit luminescence, that of the smaller specimen being particularly brilliant. This suggests that the pale yellow colour exhibited by these specimens is due to the absorption at the violet end of the spectrum associated with luminescence.

The most remarkable case of all is the yellow fluorspar which exhibits a bright luminescence exhibiting a colour similar to that of the specimen itself.

Floral colours and their origins*

SIR C V RAMAN

ABSTRACT

A new orientation is given to the subject of floral colours by the author's discovery that these colours may be placed into two distinct spectral categories, which have been designated by him respectively as the spectrum of florachrome A and of florachrome B. Typical of these two categories are the colours of *Delphinium ajacis* (Larkspur) in the blue and pink varieties respectively, the former showing the spectrum of florachrome A and the latter that of florachrome B. As a general rule, all blue flowers exhibit the spectrum of florachrome A which consists of three distinct and clearly separated bands of absorption appearing respectively in the red at $630\text{ m}\mu$, in the yellow at $580\text{ m}\mu$ and in the green at $540\text{ m}\mu$. The spectrum of florachrome B also consists of three distinct bands of absorption, but these now appear in the orange-yellow at $590\text{ m}\mu$, in the green at $545\text{ m}\mu$ and in the blue-green at $505\text{ m}\mu$. Spectra exhibiting these features are reproduced with the paper. Their explanation is discussed and it is shown that they owe their origin to an electronic absorption frequency located at the first of the three bands combining with vibrational transitions, the oscillator being the CO group present in the structure of the florachrome.

1. Introduction

The colours which flowers exhibit when held in bright sunlight represent the physiological perception of the radiation which emerges from their petals after suffering diffusion and absorption within their substance. The spectral characters of the light emerging from the petals and the physiological characteristics of human vision which determine the sensation produced by the composite radiation have alike to be taken into consideration. Any discussion of floral colours which ignores either of these determining factors, would not only be futile but may also lead one to erroneous conclusions.

The processes of absorption and diffusion suffered by light in its passage through the petals and its emergence therefrom are determined by the nature and condition of the materials present within the living substance of the flower. It follows that no inference regarding these materials can be valid or sustainable unless it is based on their optical and spectroscopic behaviours observed *in vivo*. If one attempts to extract from the flowers the materials responsible for the

* This was the subject of the Presidential Address to the 34th Annual Meeting of the Indian Academy of Sciences at Ahmedabad on Sunday, the 22nd of December, 1968.

observed colours, it is necessary to use processes which do not fundamentally alter their nature. In particular, if a solvent is used for the extraction, it should be such that it does not produce an observable change in the optical properties or spectroscopic behaviour of the pigment.

When one examines the voluminous literature in which the subject of floral colours and their origin has been dealt with, one fails to find any recognition of the fundamental considerations set forth in the two preceding paragraphs. The identification of the materials responsible for the colours of flowers as "anthocyanins" and the explanations put forward for the great differences in colour exhibited by various flowers are thereby rendered highly dubious. In treatises on plant biochemistry, the anthocyanins are placed in the general category of "flavonoids". The parent substance which gives the name to this group of organic compounds is flavone and it is a significant fact that this substance is itself a colourless solid which melts at 97° . How such a substance can be transformed into the brilliantly coloured floral pigments merely by hydroxylation and combination with glucose or other sugar residues is a mystery which one seeks in vain for an elucidation in the chemical literature.

From what has been stated above, it is evident that the origin of the vivid colours exhibited by many flowers *in vivo* has so far remained an unsolved problem. The present investigation addresses itself to finding an answer to the highly interesting questions arising in this field.

2. Florachrome A

A new orientation is given to the subject of floral colours by the author's discovery that the spectral character of the light emerging from the petals of flowers is related to the observable hue of the flowers in a highly characteristic fashion. We may illustrate this finding by a reference to some cases studied by him in earlier years.

The well-known avenue tree known botanically as *Jacaranda mimosifolia* bears numerous clusters of bluish-purple bell-shaped flowers. The climbing plant *Thunbergia grandiflora* bears large and widely expanded flowers of a pale blue colour. The well-known shrub *Plumbago capensis* commonly used as a hedge plant bears clusters of small flowers which are azure-blue in colour. Examination through a pocket spectroscope reveals that the spectra of the light diffused by or transmitted through the petals in all these three cases are very similar, viz., three distinct absorption bands well-separated from each other one in the red region of the spectrum at about $630\text{ m}\mu$, another in the yellow region at about $580\text{ m}\mu$ and a third in the green at about $540\text{ m}\mu$. Holding two petals of the *Thunbergia* flowers together and viewing the light transmitted through them with the spectroscope, all the three bands are very clearly seen, the bands in the red and in the yellow being very conspicuous and the band in the green much less so. The absorption by

the flowers of *Plumbago capensis* is very weak, but the bands are well seen when a bunch of the flowers held together is viewed through the spectroscope. It should be mentioned that in none of the three cases is there any sensible weakening of the blue region of the spectrum.

We next consider three other cases in which the observed colours are more vivid. The first is of the tree *Solanum grandiflorum* which bears large flowers of a deep bluish-mauve colour. The next is the climbing plant *Clitoria ternata* (also known as the Butterfly Pea), which bears curiously shaped flowers which in one variety are deep blue in colour. The third case is that of the plant *Meynia erecta*, which bears funnel-shaped open-mouthed flowers. One variety of this shrub bears flowers which are a deep purplish-violet in hue. In all three cases, the absorption spectrum as viewed either by the transmitted or by diffused light exhibits three bands which appear respectively in the red, yellow and green regions of the spectrum. As is to be expected, the bands as seen with these flowers are more conspicuous than with the less vividly coloured flowers mentioned earlier.

It is unnecessary here to list more flowers displaying absorption spectra of the same kind, as they will be referred to later on. The examples cited are sufficient to justify the statement that the origin of the colours displayed is the presence in the flowers of a material with the stated spectral behaviour, viz., three distinct absorption bands appearing respectively in the red, yellow and green regions of the spectrum. The three bands in its absorption spectrum are very clearly seen in figure 1. Figure 1(a) is the comparison spectrum of white light, while figures 1(b) and (c) recorded with different exposures are absorption spectra of an aqueous extract from the blue larkspur obtained in the manner later to be explained.

3. Florachrome B

The author's study of floral colours in other cases led to the discovery of another material which will be here designated as florachrome B which also exhibits three absorption bands, but these now appear respectively in the orange-yellow, green and blue-green regions of the spectrum. A particularly fine example of a flower exhibiting the three absorption bands in the stated region is the terrestrial orchid known botanically as *Spathoglottis plicata*. This orchid is very hardy and may be grown in pots like any other plant. It has elongated leaves and bears a great many racemes of flowers on erect spikes of considerable length. Being always in bloom, it is available at all times for observation of the very striking nature of the absorption spectra of the flowers. Each flower has five petals which are well-separated from each other, so that any one of them can be viewed without being detached from the rest. The colour of the petals is a vivid purplish-red and the absorption spectrum which gives rise to this colour is most conveniently studied by holding the flower in a strong light and viewing the selected petal through a

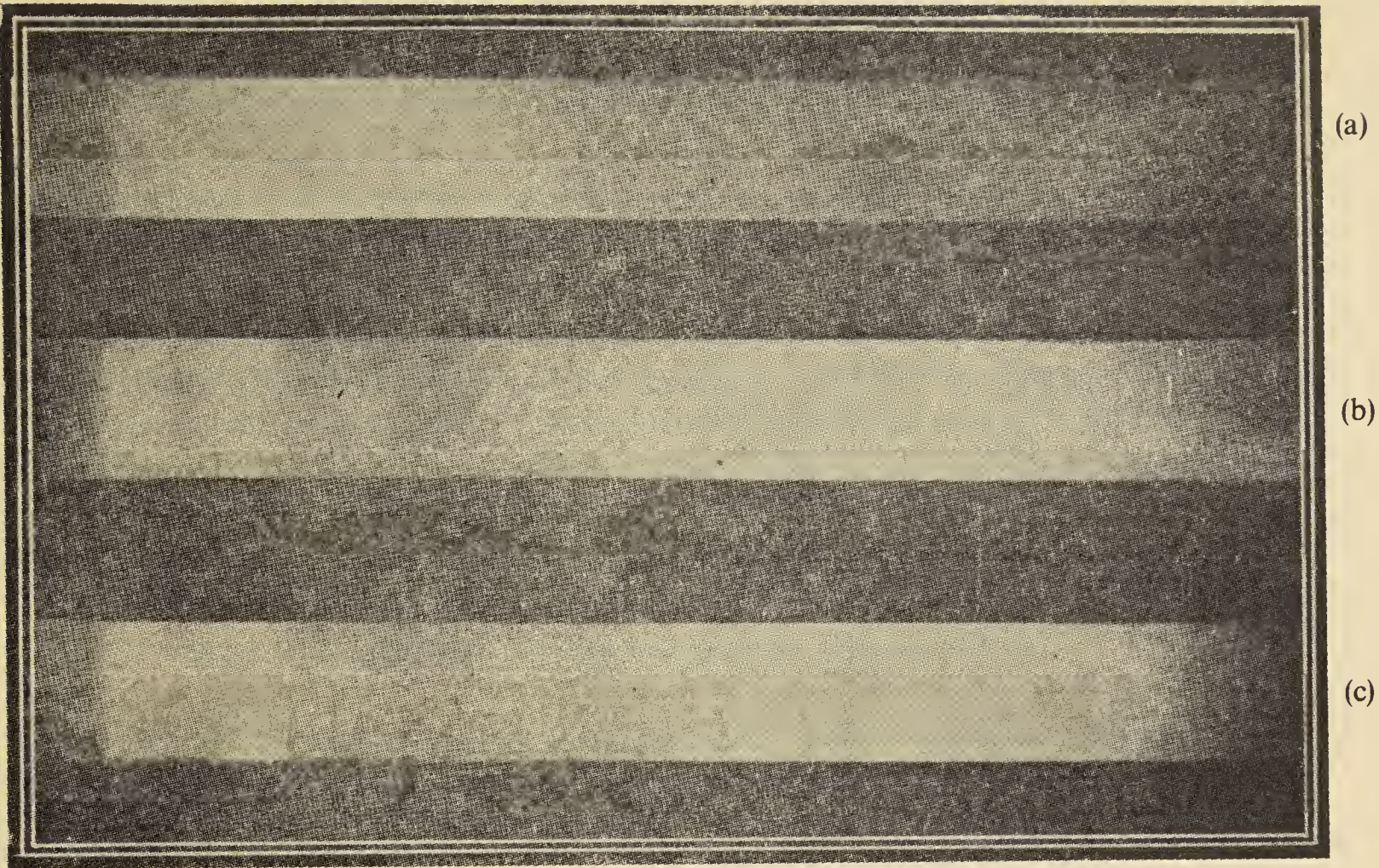


Figure 1. Absorption spectra of florachrome A.

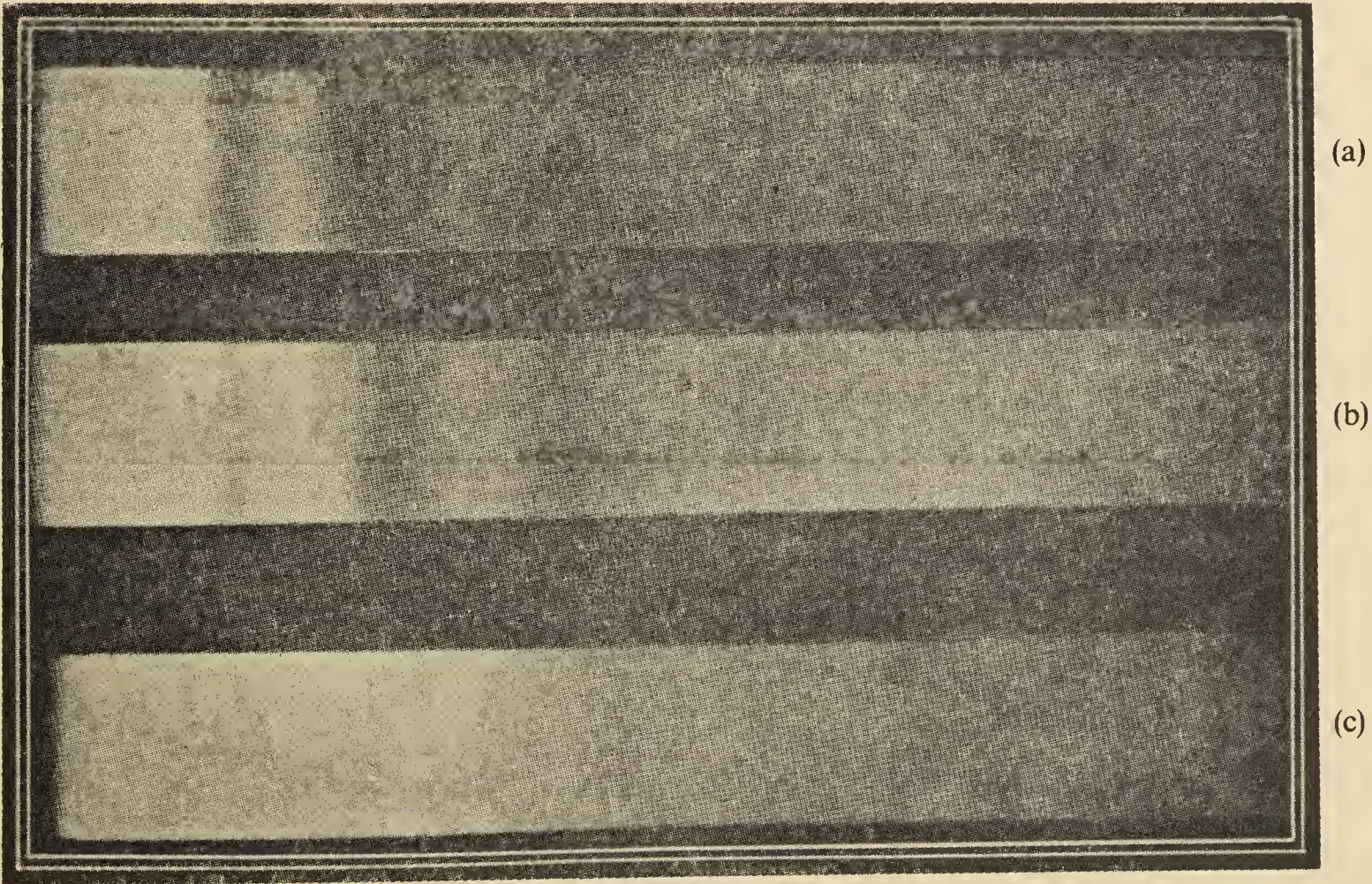


Figure 2. Absorption spectra of florachrome B.

pocket spectroscope held not too far away from it. The spectrum of the light diffused by the petal as thus observed exhibits *a nearly complete extinction of the orange-yellow region of the spectrum from 580 to 600 m μ* . Another dark band is conspicuous between 540 and 550 m μ , but it is not one of complete absorption. A third and comparatively faint absorption is visible between 500 and 510 m μ . The red region of the spectrum is seen with full strength. There is also no observable weakening of the blue region of the spectrum. Figure 2 reproduces the absorption spectra of a petal of *Spathoglottis plicata* recorded by placing the petal before the slit of a wavelength spectrometer. Figures 2(a) and (b) reproduce the spectra thus obtained with different exposures, while figure 2(c) is the comparison spectrum of white light.

4. Some colourful garden plants

The role played by the two florachromes in the production of the observed colours of flowers is very well illustrated by the case of *larkspur*. This is a favourite garden plant belonging to the botanical category *Ranunculaceae*. Gardening books describe the larkspur as "a very showy annual, freely producing spikes of beautiful flowers, available in blue, lilac, purple, white and pink shades." The plant grows well at Bangalore and the flowers which are available fall into two clearly defined groups. One of the groups may be described as exhibiting blues and bluish-purples of various shades. The other group exhibits a pink colour ranging from a bright to a very light shade of that hue. Spectroscopic examination of the light diffused by the petals of the first group reveals that they owe their colour to florachrome A. Likewise, it is found that the flowers of the other group owe their colour to florachrome B. In either case, the deeper the colour, the more pronounced are the absorption bands, thereby indicating that the intensity of the perceived colour is determined by the quantity of florachrome present in the petals.

The spectra of florachrome A and florachrome B are vividly exhibited by the flowers of *Cineraria* which is classed botanically as belonging to the *Compositae*. Gardening treatises describe the *Cineraria* as "beautiful pot plants which are showy with their large luxuriant leaves surmounted by immense panicles of magnificent flowers of most brilliant colours; the blooms last for quite a long time, nearly a month." The colours are observed to fall into two groups, one group ranging between a light blue and a dark violet, and another from a light to a deep purplish-red. Spectroscopic examination reveals that the flowers of the first group exhibit the spectrum of florachrome A and those of the second exhibit the spectrum of florachrome B. As is to be expected in view of the brilliance of the colours, the absorption bands are highly pronounced and are indeed very striking.

Delphinium is another garden plant which is of great beauty. Its flowers appear arranged along spikes, the colours ranging from a delicate blue to a dark purple or violet. In every case, the petals exhibit the spectrum of florachrome A, the strength of the absorption bands increasing with the depth of the colour exhibited by the flower.

Iris germanica, also known as Flag Iris, has sword-like leaves and bears flowers on erect stalks. It is a hardy and vigorous plant and the flowers which are curiously constructed have gorgeous colours, one of the most attractive varieties being that in which flowers are purplish-blue. The petals of the flower are very thin, and hence it is desirable to hold two of them together and examine the light transmitted by them to observe the absorption bands. Here again, we notice three well-separated bands and recognise the spectrum as that of florachrome A.

Petrea volubilis is classed botanically amongst *Verbenacae*. It is a climbing plant which requires a support on which it can spread out. It bears purple star-like flowers in large elegant wreath-like sprays. Racemes of flowers crowd the plant covering it with a mass of purple-blue colour. Holding a bunch of the flowers in sunlight and comparing the spectrum of the light diffused by their petals and by a sheet of white card held below, it becomes evident that there is practically complete extinction of the yellow part of the spectrum, besides a noticeable weakening of the red region. The blue sector, on the other hand, shows up quite strongly. It is evident that the bluish-purple colour exhibited by the sprays of *Petrea volubilis* is due to florachrome A present in the petals.

Asters belong to the botanical group known as the *Compositae*. They bear very showy flowers, exhibiting numerous petals arranged around a common centre. The varieties which are grown extensively at Bangalore as a commercial proposition for export to other parts of India exhibit brilliant colours. These flowers are readily available for study. They show a great range of hues. A considerable proportion exhibit colours ranging from a light pink to a deep red or crimson. There is another group of flowers whose colours range from a light bluish-purple to a deep colour which may be termed as violet. Holding the flowers in sunlight and viewing them through a pocket spectroscope, their optical behaviour may be compared with that of a white card below, and several remarkable facts come to notice. Particularly interesting is that there is no noticeable difference between the two groups of flowers in respect of the blue sector of the spectrum which is conspicuous in the spectrum of the diffused light in both cases. But the two groups differ markedly in other respects. With the blue flowers, the red sector of the spectrum is much weakened and it also shows an indication of being divided into two by an absorption band running through it. A dark absorption band also covers the yellow sector while the green remains fairly bright. On the other hand, the flowers which range in colour from pink to crimson show the red sector of the spectrum in full strength. But the yellow and green sectors are both much weakened. These features are readily understood when it is recognised that the colours of the blue asters are ascribable to florachrome A and those of the red asters to florachrome B.

5. The isolation of the floral pigments

Treatment by immersion either in dilute acids or in dilute alkalies has a destructive effect on the florachromes. This becomes evident when, for example, the blue petal of delphinium is immersed in dilute hydrochloric acid. The petal changes to a bright red colour, and examination through a pocket spectroscope reveals that the discrete absorption bands due to florachrome A have disappeared. The discoloured petal shows a spectrum in which the green sector is nearly extinguished and the yellow is weakened, while the red sector appears in full strength. Immersion of a petal of delphinium in dilute ammonia results in its changing colour from blue to a greenish-blue. The discrete bands disappear and this spectral regions of red and yellow appear with greatly reduced intensities, while the green continues to be full strength. The purplish-red petals of *Spathoglottis plicata* which exhibit the absorption spectrum of florachrome B change colour to an orange-red on immersion in dilute HCl. The discrete absorption bands disappear and the green sector of the spectrum is nearly extinguished, while the yellow and red sectors appear with normal strength. The petal of the same orchid when treated with dilute ammonia changes colour from a purplish-red to a greenish-blue. The discrete absorption bands disappear and while the green of the spectrum retains its full strength in the transmitted light, the red and yellow sectors become extremely weak. Examples of this kind may be indefinitely multiplied to show that the effect of acids and alkalies on flower petals is fundamentally to alter their spectroscopic behaviour.

In view of the facts stated above, it is scarcely possible to accept the view that the anthocyanins prepared by the methods usually adopted by organic chemists are the pigments responsible for the colours exhibited by flowers *in vivo*. It is, of course, of great interest to isolate these pigments from the flowers so that their behaviour can be studied *in vitro*. But for these purposes, as has already been stated in the introduction, it is necessary to adopt methods which do not fundamentally alter the optical properties and spectroscopic behaviour of the pigments. Such methods are indeed available.

In many cases, it is possible to obtain an extract of the floral pigment merely by grinding a few moist petals to a fine paste in an agate mortar and then adding a little water and filtering the product through a loose plug of cotton-wool into the observation cell. The aqueous solution of the floral pigment thus obtained is often of considerable strength and may have to be diluted to obtain the desired degree of transparency. Using a longer or shorter cell to hold the extract also enables the strength of the transmitted light to be controlled.

A second and generally useful method is to place a sufficient quantity of the flower petals in a flask and to pour in some acetone to cover the petals. Vigorous shaking results in the pigment being extracted by the acetone and a solution of adequate strength being obtained which can be transferred to an observation cell. In those cases where the extraction by the acetone proceeds too slowly, it can be

speeded up by warming the flask, or if necessary by heating it till the acetone begins to boil.

The extraction of the floral pigment by the method first described is evidently to be preferred as it is a purely physical process which would not result in any alteration of the structure and properties of the florachrome. Indeed, the aqueous solutions obtained by that process show a spectroscopic behaviour similar to that of the petals themselves. It should be mentioned however that the extract may include some colloidal material which has passed through the filtering plug of cotton-wool and diminishes its transparency to light.

The extraction of the pigment with the aid of acetone is generally both quick and convenient, and if the petals used are quite clean, the solution obtained is free from colloidal matter and exhibits the maximum transparency. The method has the advantage that by adjusting the quantity of material put in and the volume of acetone made use of, it is possible to obtain extracts which show the absorption bands in satisfactory strength, viz., more petals and less acetone for weakly pigmented flowers, and fewer petals and more acetone for strongly pigmented ones. The spectroscopic behaviour of the pigment can then be observed in more satisfactory conditions than with the petals themselves. It should be mentioned, however, that the acetone extracts do not always reproduce exactly the spectral behaviour of the petals. It is noticed that the relative intensities of the absorption bands are altered, and their positions may also exhibit observable shifts.

6. Visual perception of colour

We proceed to consider how the observed colours of the flowers are related to the spectral characteristics of the florachromes. A few remarks are necessary here regarding the composition of white light and the visual effects produced by the different parts of its spectrum. The relative luminosities of the various regions of the spectrum depend to a great extent on the absolute level of brightness at which the observations are made. At the fairly high levels with which we are here concerned, the most luminous part of the spectrum is the yellow sector, the limits of which may be indicated as from 560 to 600 $m\mu$. Its great influence on our visual perceptions is readily demonstrated by viewing a brilliantly illuminated area of white light through a filter of glass doped with neodymium oxide which cuts out the spectral region between 570 and 600 $m\mu$ completely, but has very little effect on the rest of the spectrum. An enormous reduction of visual brightness is found to result from holding such a filter before the eye. It is a consequence of this characteristic of our visual sensations that the exclusion of the yellow sector in the spectrum by absorption is necessary for the other parts of the spectrum to manifest themselves strongly in the perception of colour. Indeed, extensive studies demonstrate that no object can appear brilliantly green or blue or red

unless the yellow of the spectrum has been much weakened or totally excluded from appearing by absorption.

In view of what has been stated, the role of the florachromes in the production of visible colour is readily understood. Both florachrome A and florachrome B exercise a strong absorption on the yellow sector of the spectrum. Further, florachrome A also exercises a noteworthy absorption in the red sector of the spectrum, while florachrome B does not exhibit such absorption, but on the other hand has an absorption of significant strength in the green sector of the spectrum. A large reduction in the strength of the yellow sector and the enfeebling of the red and green sectors would enable the blue sector to manifest itself and by masking the rest of the spectrum to become the dominant sensation. *Per contra*, a large reduction in the strength of the yellow and green sectors would enable the red sector to mask the rest of the spectrum and become the dominant colour. For such effects to be manifested to the maximum extent respectively by florachrome A and by florachrome B, it is necessary that they should be present in the petals in adequate quantities.

That the absorption of light appearing in the yellow sector of the spectrum plays a highly important role in the perception of floral colour becomes evident when a flower is viewed through a neodymium glass filter. In all cases where the absorption of the yellow by the flower itself is incomplete, the introduction of the filter before the observer's eye completes the process and the result is an enrichment of the observed colour. For example, a pink larkspur viewed through the filter appears red. Such enrichment of the observed colour becomes a spectacular phenomenon when a tree enveloped by a mass of its flowers is viewed through the neodymium filter. Two examples of such trees may be mentioned here. One of them is *Milletia ovalifolia*, which in the flowering season bears great masses of tiny flowers of a lilac colour. They make the tree a conspicuous object even from a distance. The interposition of the filter results in a very striking intensification of the massed colour of the flower-laden branches which then appear of a reddish-purple colour. Another case is that of *Tabebuia guayacan* which is one of the loveliest of ornamental trees, bearing lilac-coloured flowers in the form of bunches or bouquets. Seen through the filter, these flowers turn to a rich red hue. Similar effects are exhibited by all flowers in which florachrome B functions but is not present in sufficient quantity to produce its maximum effect. Likewise, in all cases where florachrome A functions but the resulting colour is not very intense, the introduction of the filter produces a readily observable effect.

7. The spectra of the florachromes

It may be stated as a general rule that flowers which exhibit a blue colour contain florachrome A which is responsible for that colour being perceived. The more intense the colour, the greater is the quantity of the florachrome present, as may

be demonstrated by the methods of extraction described above. In such cases, also, the three bands of absorption in the spectrum which are characteristic of florachrome A are conspicuously visible in the light diffused by the petals. Their positions can be approximately determined by observation through a direct vision spectroscope provided with a wavelength scale. A few such measurements are listed below:

Blue larkspur	630 m μ , 580 m μ , 540 m μ
<i>Delphinium</i>	630 m μ , 580 m μ , 540 m μ
<i>Solanum grandiflorum</i>	630 m μ , 580 m μ , 540 m μ
<i>Meynia erecta</i>	630 m μ , 580 m μ , 540 m μ

It will be noticed that the positions of the bands in the four cases listed are not observably different, and this is clear evidence that we are concerned with a material with specific properties appearing in flowers of totally different origin. In all four cases, the first band appearing in the red is the most conspicuous, while *per contra* the third band appearing in the green is weak and diffuse. These observations suggest that the band of the greatest wavelength represents the principal absorption of the material and that the other two bands arise from combinations of the principal electronic frequency with vibrational transitions. The differences in the wave number of successive bands are about the same and may be put as 1325. This may be regarded as the vibration frequency of the florachrome A.

As has already been stated, the complete spectrum of florachrome B is shown with admirable strength and sharpness by the terrestrial orchid *Spathoglottis plicata*. It is also shown vividly by several orchids of a purple colour and sundry other plants which have come under observation by the author. The bands of florachrome B are shown with special intensity by the flowers of *Cineraria* which display a purplish-red colour. The first two of the three bands can also be recognised in the spectrum of the pink larkspurs. They are as noted below:

<i>Spathoglottis plicata</i>	590 m μ , 545 m μ , 505 m μ
<i>Cineraria</i> (purplish-red)	600 m μ , 550 m μ , 510 m μ
Larkspur (pink)	590 m μ , 545 m μ , —

As in the case of florachrome A, the first band in florachrome B which here appears in the orange-yellow region of the spectrum is the most conspicuous, while, *per contra*, the third band appearing in the green-blue region is weak and diffuse. The same suggestions as those made above for florachrome A can also be put forward regarding the relationships between the three bands exhibited by florachrome B. The differences in the wave number of the successive bands are about the same and may be put as 1425, which is the vibration frequency of florachrome B.

Since the absorption bands of florachrome B appear in the yellow and green sectors of the spectrum, these sectors appear with much reduced intensity, and as

already mentioned, the result is that the red sector of the spectrum becomes dominant and determines the observed colour of the flower. The quantity of the florachrome B present determines the strength, in other words, the degree of saturation of that colour. This is well-illustrated by the case of *Spathoglottis plicata*, the commonest variety of which bears flowers which are of a vivid purplish-red colour. There is another variety of the same plant, the flowers of which are of a deep purplish-crimson colour. Spectroscopic examination of these flowers shows the same absorption bands but intensified in strength, so much so that the green and yellow are almost completely extinguished. It should be noted that neither variety of *Spathoglottis plicata* shows any observable weakening of the blue sector of the spectrum. It is therefore not surprising that the colour of these flowers is not a pure red or crimson but exhibits a purplish hue.

Many flowers which appear pink or red or crimson show a strong absorption of light in the yellow and green parts of the spectrum. That such absorption determines the observed colour is evident from the fact that it is deeper in the varieties which exhibit the absorption most strongly. The three bands which characterise florachrome B are not usually seen as distinct and separate regions in the absorption spectra of the petals of such flowers. We are nevertheless justified in assuming that the florachrome is present and is responsible for the observed colour. Red or crimson-roses may be mentioned as an example of such a situation. Definite proof that we are concerned in such cases with florachrome B is forthcoming when the spectrum of white light transmitted through a column of the acetone extract of the floral pigment is examined. The presence of distinct bands of absorption in the yellow, green and green-blue regions of the spectrum then becomes evident to observation.

8. The structure of the florachromes

The configuration of the anthocyanin molecules envisaged by the organic chemists is based on a grouping of atoms similar to the aromatic hydrocarbon naphthalene joined by a single bond to another grouping similar to benzene. There is however a noteworthy difference, viz., that instead of ten carbon atoms arranged round the periphery as in naphthalene, we have only nine carbon atoms and one of oxygen. Since oxygen is divalent, it is not possible to have a regular succession of alternating single and double bonds around the periphery as in naphthalene. This disturbance in the order characteristic of an aromatic molecule results in a profound modification of the structure and optical behaviour of the grouping. One of the four valences of carbon atom adjacent to an oxygen atom is engaged in the formation of what may be described as a pseudo-double bond between this carbon atom and the adjacent oxygen. This pseudo-bond is necessarily much weaker than the double bond appearing in a carboxyl group, and as a consequence, its characteristic absorption is thereby shifted and falls

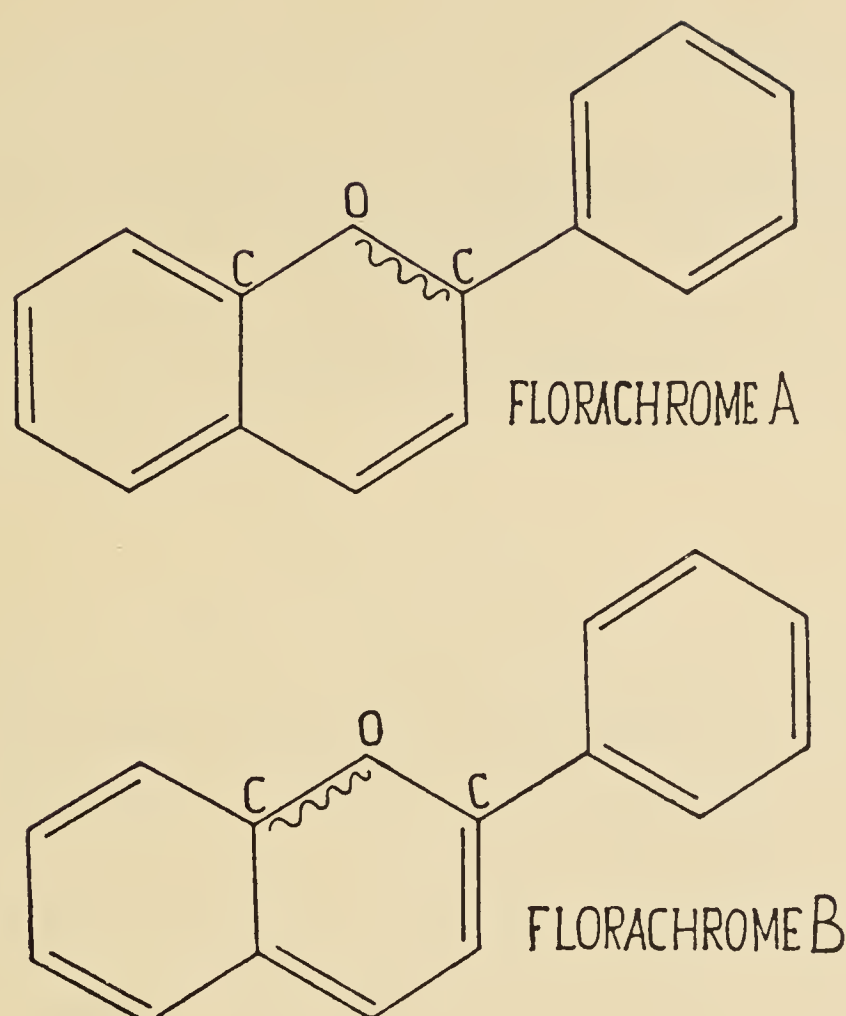


Figure 3. Structure of the florachromes.

within the range of the visible spectrum. The observable consequence is the production of visible colour. The vibration frequency of the pseudo-double bond will also be less than for a carboxyl group which is 1800 in wave numbers. Such lowering of the vibration frequency will manifest itself in a closer approach of the vibration bands to the characteristic electronic frequency. As the oxygen atom is located between two carbon atoms occupying different positions in the group, there are two distinct situations of the kind described above which are possible. These are shown separately in the accompanying diagram (figure 3). One of the two situations correspond to florachrome A and the other to florachrome B. In the latter case, the pseudo-double bond lies closer to the centre of the group and therefore presumably results in a somewhat stronger binding.

The florachromes: their constitution and optical behaviour

SIR C V RAMAN

1. Introduction

The nature of the pigments or colouring matters which are present in the petals of flowers and which are responsible for the hues which they exhibit is a subject of great interest. An important first step towards the determination of their nature makes use of a very simple procedure, which is to view the flowers held in bright sunlight through a pocket spectroscope. The spectrum of the light emerging through the petals or diffusely reflected by them when thus examined exhibits characteristic features. Certain regions in the spectrum are observed to be much weakened or even totally extinguished, while other regions do not exhibit any noticeable diminution in their intensity. The spectral regions which exhibit the absorption are indicative of the nature of the floral pigments, while those regions of the spectrum which escape such absorption and are present in the emergent diffused light determine the observed colour of the petals.

Another procedure for the study of the floral pigments which suggests itself is their extraction from the petals with the aid of suitable solvents and the spectroscopic examination of the solutions thus obtained. In following this procedure, it is obviously of the highest importance that the solvent employed does not produce any noticeable change in the constitution or optical behaviour of the pigment. Whether such a change is actually produced becomes evident on a comparison of the colour of the petals and their spectroscopic behaviour *in vivo* with the colour and spectroscopic behaviour of the solution of the extracted material. In most cases, the pigments are so firmly embedded in the structure of the petals that an attempt to extract them by placing them in a vessel containing water or methyl alcohol or ethyl alcohol, followed by vigorous shaking produces no observable result. Much more successful is the use of acetone as a solvent. In numerous cases, immersion of the petals in acetone and vigorous shaking results in a nearly complete extraction of the colouring matter. Other cases which resist such simple treatment may be successfully dealt by first grinding the petals in an agate mortar and adding a little acetone to the pulp thus obtained. Filtering the acetone extract yields a clear solution which can then be spectroscopically examined.

There are several advantages in thus studying the floral extracts instead of the flowers themselves *in vivo*. By regulating the quantity of the petals used for the

extraction and the volume of the solvent employed, the concentration of the solution can be adjusted to that best adapted for spectroscopic examination. The length of the absorbing column and the intensity of the light-beam can also be chosen suitably. Further, it is only by using the extracted material in solution that it is possible to obtain spectrophotometric records of the transmitted light with the instruments generally available. Still another advantage is that the extraction can be carried out in successive steps, thereby enabling it to reveal whether we are concerned only with one pigment or with more pigments than one differing in their solubility in various liquids.

2. The florachromes

Studies by the author adopting the techniques described above resulted in the discovery that there are two distinct categories or species of floral pigment characterised by quite different spectroscopic behaviours. In the publication announcing this discovery, the author ventured to name these categories as florachrome A and florachrome B respectively. The presence of one or of the other pigment, in greater or less quantity, is found to be responsible for the observed floral colours in numerous cases. The simultaneous presence of the two categories of pigment in diverse proportions is also found to be the explanation of many other floral colours met with in practice.

The case with which the spectral behaviour of individual flowers *in vivo* can be recognised would naturally depend on the particular circumstances of the case and especially on the quantity of the pigment present in the petals. It is evident that either too little or too much of the pigment would be unfavourable for a direct observation of the absorption spectrum in the light emerging from or diffused by the petals. It is therefore useful to mention some cases in which the characteristics of the florachromes are exhibited with the maximum clarity by the flowers themselves.

The example chosen for special mention here is *Clitoria ternata*, which bears flowers of some size. In one variety, these exhibit wide margins of a bright blue colour. The plant belongs to the botanical class *Leguminosae* and is a hardy perennial by nature, though it may be raised and grown as an annual from seeds. Commonly known as the Butterfly-Pea, it is to be found in many Indian gardens. Viewed through a spectroscope in bright light, the blue areas exhibit a characteristic three-banded spectrum, the most striking feature of which is an intense absorption at about $630\text{ m}\mu$, followed by another distinctly less intense absorption at about $575\text{ m}\mu$, and a very weak and diffuse band at about $530\text{ m}\mu$. As the result of the first two absorptions, the entire spectrum between 630 and $575\text{ m}\mu$ is seen with much reduced intensity. It is thus evident that the observed bright blue colour of the flower is a consequence of the reduced intensity of the orange and the yellow regions in the spectrum of the light diffused by its petals.

The pigment responsible for the observed blue colour of *Clitoria ternata* is readily extracted by simple immersion of its petals in acetone. A tube 5 cm long containing the blue extract shows the same features in its spectrum as the petals themselves, but more conspicuously.

A particularly fine example of the absorption spectrum of florachrome B exhibited with the maximum of clarity is furnished by the terrestrial or ground orchid known botanically as *Spathoglottis plicata*. This is a very hardy plant which may be grown in pots like any other garden plant. It flowers profusely at all seasons of the year, bearing racemes of flowers on erect spikes of great length. The material is therefore available in quantity for examination at all times. The petals exhibit a purplish-red colour, and the spectrum exhibits a three-banded structure but this differs from that of florachrome A. The most intense of the three absorption bands is located around $590\text{ m}\mu$ and completely obscures the yellow region in the spectrum. A second band of distinctly lesser intensity is located in the green around $540\text{ m}\mu$. A third band which is rather faint appears in the blue-green region of the spectrum around $510\text{ m}\mu$. The region of still smaller wavelengths exhibits no noticeable absorption. It is evident that the extinction of the yellow and the weakening of the green regions in the spectrum are responsible for the observed colour of the flower.

The floral pigment is readily extracted from the petals of the orchid *Spathoglottis plicata* by immersing them in a beaker containing acetone. The extract exhibits a purplish-red colour and the spectrum of the light transmitted by it exhibits features similar to those of the flowers *in vivo*. But there is an observable change in the relative intensities of the bands. The band in the green appears somewhat more intense than the band in the yellow as seen in the spectrum of the acetone extract.

Spectrophotometric records of the absorption spectra of the acetone extracts from *Clitoria ternata* and from *Spathoglottis plicata* are reproduced respectively as figures 1 and 2. The wavelengths shown were roughly estimated from their positions on the recorded chart, and lay no claim to precision. But the reproduced curves should be sufficient to convince any one that two florachromes actually exist exhibiting different spectrophotometric behaviours.

As an example of a flower of which the observed colour is due to the co-existence of both the florachromes, we may cite the case of the blue iris (*Iris germanica*). The curiously shaped flowers of this plant have petals of a purplish-blue colour. But this is not a deep or saturated colour, and it is therefore not surprising that spectroscopic examination of the light diffused by the petals shows only weak and ill-defined bands. Examination of the light transmitted through two petals held together however exhibits the bands more distinctly. In particular, the absorption band in the yellow region can be seen, and the presence of an absorption band in the red region is also evident. Immersion of the petals of the blue iris in acetone results in the immediate extraction of a solution which exhibits a purplish-red colour, which the spectroscope reveals as due for the most

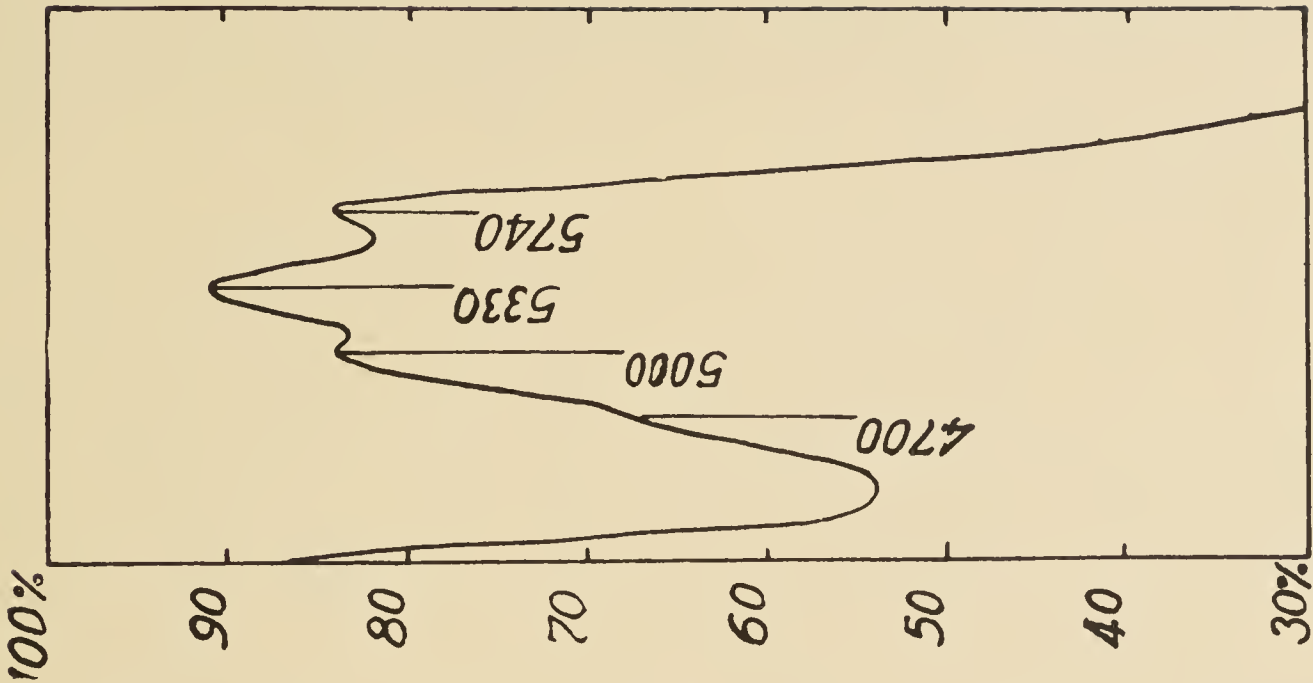


Figure 2. Absorption spectrum of *Spathoglottis plicata*.

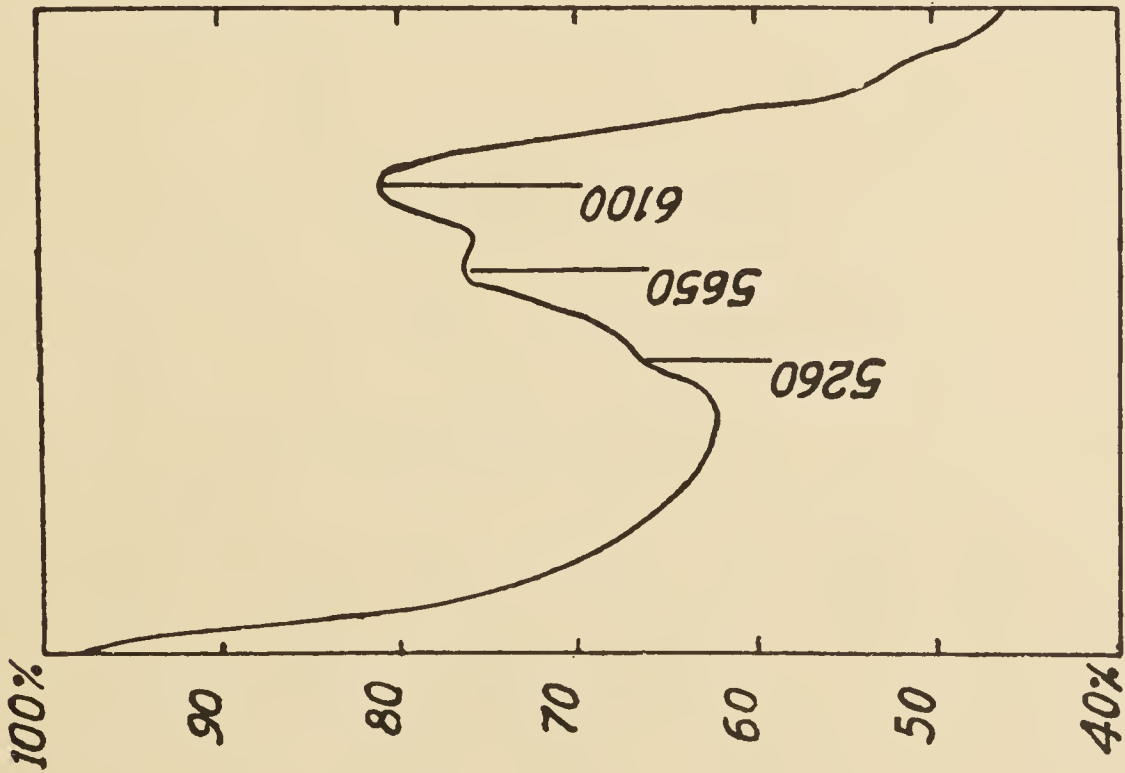


Figure 1. Absorption spectrum of *Clitoria ternata*.

part to the presence of florachrome B. The residue left after the acetone extraction when stirred in water yields a blue solution which the spectroscope reveals as due to the presence of florachrome A. Similar results have been obtained with many other flowers. In these cases, the acetone extract from the petals either in the natural state or after being ground to a pulp in an agate mortar is a purplish-red solution exhibiting the absorption spectrum of florachrome B, while the residue when stirred up with water gives a blue solution showing the absorption spectrum of florachrome A.

We now proceed to consider the explanation of the spectra of the two florachromes in terms of their chemical constitution. Though the spectra are quite different, they exhibit a measure of similarity which indicates that they are substances of the same general nature which differ only in the specific configuration of the centres responsible for the absorption of the light by the molecules of the pigment. The triplet band observed in both the cases is readily interpreted as due to the electronic absorption by a CO group in the structure giving the most intense line of the triplet, while its two other weaker and more diffuse companions represent its combinations with vibrational transitions. The three possible structures of a molecule of the pigment are represented as (a), (b) and (c) respectively in figure 3. If (a) and (b) are superposed on each other, we have an absorbing centre where the CO group remains in the same position throughout. On the other hand, if (b) and (c) are superposed, the CO occupies two positions alternately. The electronic energy of the CO group would obviously be

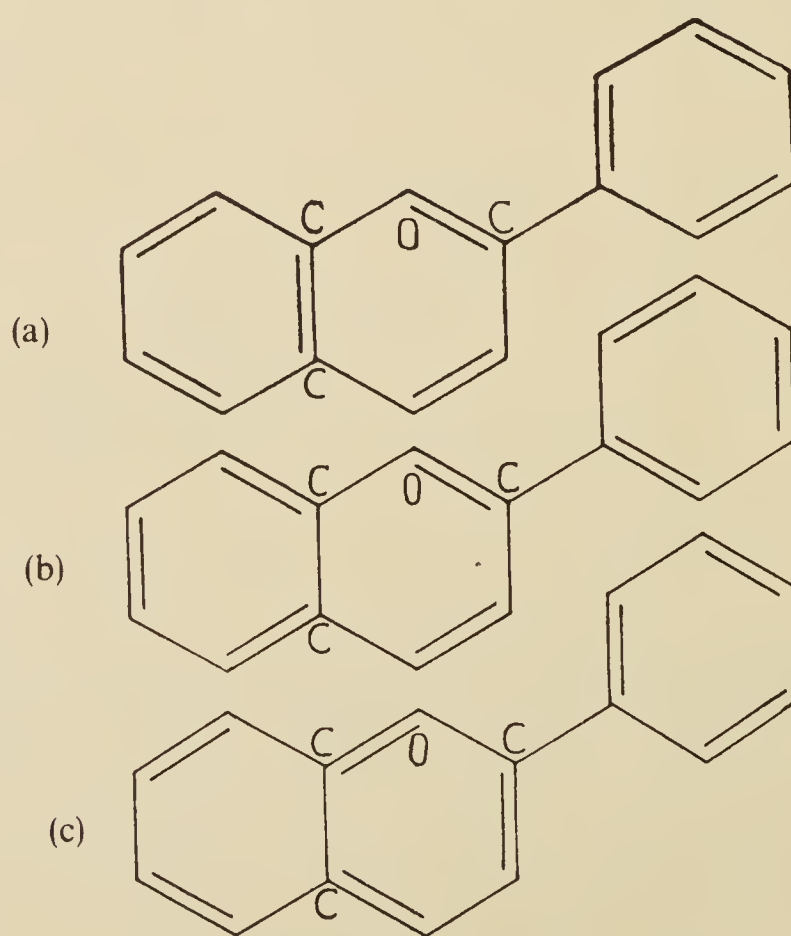


Figure 3. Chemical constitution of the florachromes.

different in the two cases. We may identify the superposition of (a) and (b) as giving us florachrome A, and the superposition of (b) and (c) as giving florachrome B, which has the higher electronic energy.

The spectrophotometric records reproduced as figures 1 and 2 were made in the Instruments Section of the Indian Institute of Science to whose authorities the thanks of the author are due.

The colours of roses

SIR C V RAMAN

ABSTRACT

A spectrophotometer record of the absorption spectrum of an acetone extract of the pigments of a red rose is reproduced. It exhibits three peaks respectively in the yellow, in the green and in the greenish-blue regions of the spectrum, thereby indicating the identity of the pigment as florachrome B. The features observed in the record enable it to be inferred what colours a rose would exhibit if it contained varying quantities of the pigment. These are in agreement with the facts of observation.

1. Introduction

The popularity of the rose has led to great efforts being made towards the development of varieties exhibiting diverse habits of growth and flowering and especially those producing large blooms with numerous petals and attractive colours. Hundreds of named varieties have thus been created and widely distributed. They are to be found listed and illustrated in several publications. The colours which are forthcoming are so striking and so varied that considerable interest attaches to the problem of their origin.

The first step towards the elucidation of these colours is to classify them into distinct groups. We may begin with some familiar colours, viz., yellow, orange, scarlet, red and crimson—limiting ourselves to those cases in which these colours exhibit the maximum degree of saturation or fullness. But not all roses can thus be described. Many present similarity in colour to spectral yellow, orange or red, but are of less saturated hues. Other colours, again, bear no resemblance to any of the pure spectral colours. Various special names have been given to rose colours, viz., cream, pink, salmon, vermilion, mauve and lilac. To this list must be added the multi-coloured roses which display different colours on the front and reverse faces of the petals, e.g., scarlet and yellow, or red and white, while others present areas different in colour on the same side of the petals.

2. The genesis of the colours

We are chiefly interested here in the chemical problem, in other words, with ascertaining the nature of the pigments present in the petals which absorb the

light rays incident on them, the rays which escape such absorption and emerge as diffused light determining the observed colours. Observation of the flowers held in sunlight through a pocket spectroscope reveals that roses exhibiting vivid colours such as scarlet, red or crimson completely absorb most of the visible spectrum, allowing only limited regions of it to escape as diffused light. Similar observations with the less vividly coloured roses indicate only the parts of the spectrum which suffer the greatest measure of absorption. Thus, in either case, the information which is forthcoming does not enable any definite conclusions to be arrived at regarding the absorptive properties of the pigment over the entire range of the visible spectrum.

In these circumstances, it becomes necessary to rely on the study *in vitro* of the pigments extracted from the rose petals by solvents which do not fundamentally alter their optical behaviour. The two solvents which have been employed in the author's studies are ethyl alcohol and acetone respectively. Rose petals immersed in ethyl alcohol are bleached and given sufficient time become practically colourless. With yellow roses, or with multi-coloured roses exhibiting yellow faces or sectors, the alcoholic solution exhibits a golden-yellow colour. On the other hand, the alcoholic extract of other roses is quite colourless, from which we infer that the pigment responsible for the colour of such roses has gone into solution, but has simultaneously been transformed into a colourless product.

Rose petals immersed in acetone behave differently. Yellow roses, and the yellow areas in multi-coloured roses are not immediately affected. But roses of all other colours and the areas on multi-coloured roses exhibiting colours other than yellow are quickly decolourised, and as the pigment is extracted from the petals, it dissolves in the acetone which then acquires its colour. The acetone extract may then be transferred into an observation tube with flat ends. Viewed against a bright source of white light through a pocket spectroscope, the absorption spectrum of the solution is seen by the observer. The concentration of the acetone extract can be varied by using fewer or more petals as the case may be and adjusting the quantity of acetone used for the extraction. It is also useful to have observation tubes of greater or shorter length, as may be found desirable, depending on the strength of the coloured extract.

Observations made in this manner with the acetone extracts reveal that the extracted material is much of the same nature in all the cases which have been studied by the author. Crimson roses, red roses, scarlet roses, orange roses and roses which are a light pink or a deep pink, all present spectra which are very similar in appearance. The long wavelength region in the spectrum extending from $600\text{ m}\mu$ upto the red end comes through in full strength. But the yellow and green sectors of the spectrum between 600 and $500\text{ m}\mu$ are strongly absorbed. Darker bands in which such absorption is a maximum are clearly visible respectively in the green and yellow parts of the spectrum. There is also an observable transmission of light in the blue region of the spectrum.

The alcoholic extract from yellow roses examined spectroscopically exhibits an

absorption which covers the short-wave end of the spectrum and extends a little beyond the blue upto about $515\text{ m}\mu$.

3. Spectrophotometric study

Figure 1 is the spectrophotometric record obtained with the acetone extract from a rose of a deep red colour held in a cell of 1 cm thickness. The figures entered are wavelengths in \AA . The extract had to be diluted with acetone to enable the nature of the absorption to be clearly recorded. It will be seen that the record exhibits three distinct humps appearing respectively in the yellow, in the green and in the blue-green regions of the spectrum. These features exhibited by the record indicate that the pigment responsible for the colour of the red roses may be identified with the material designated by the author as florachrome B.

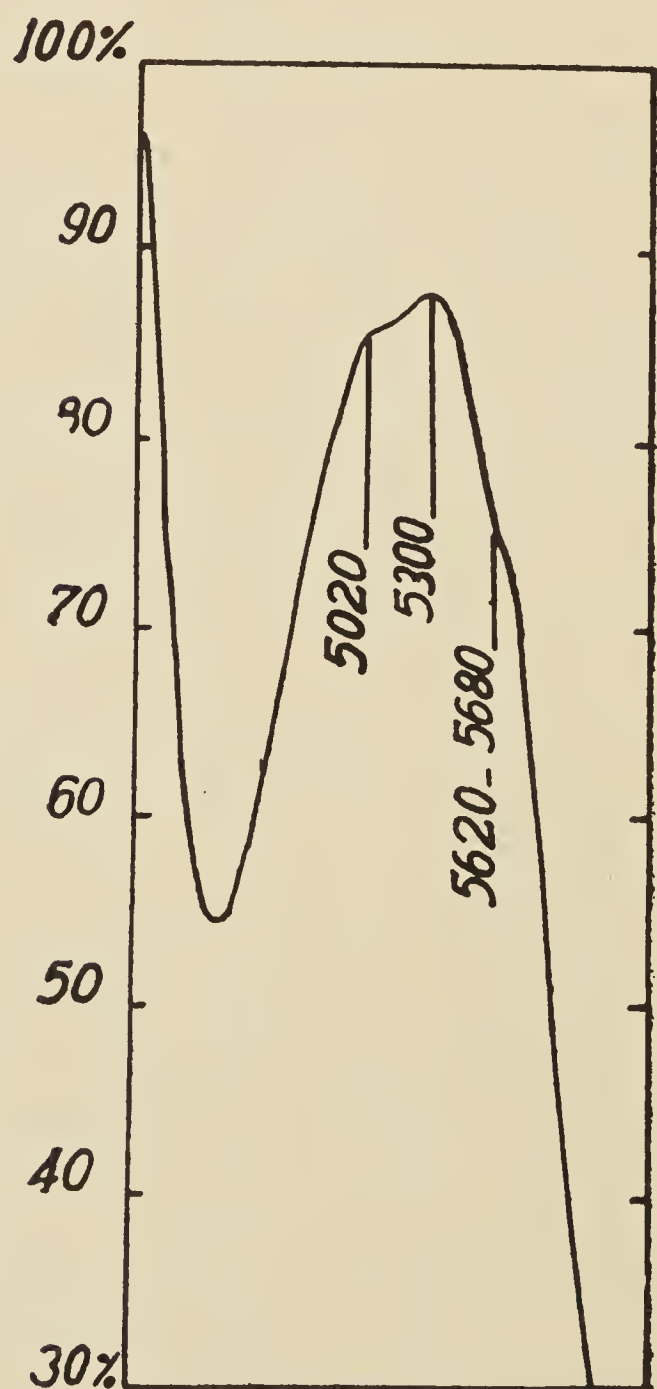


Figure 1. Absorption spectrum of red rose.

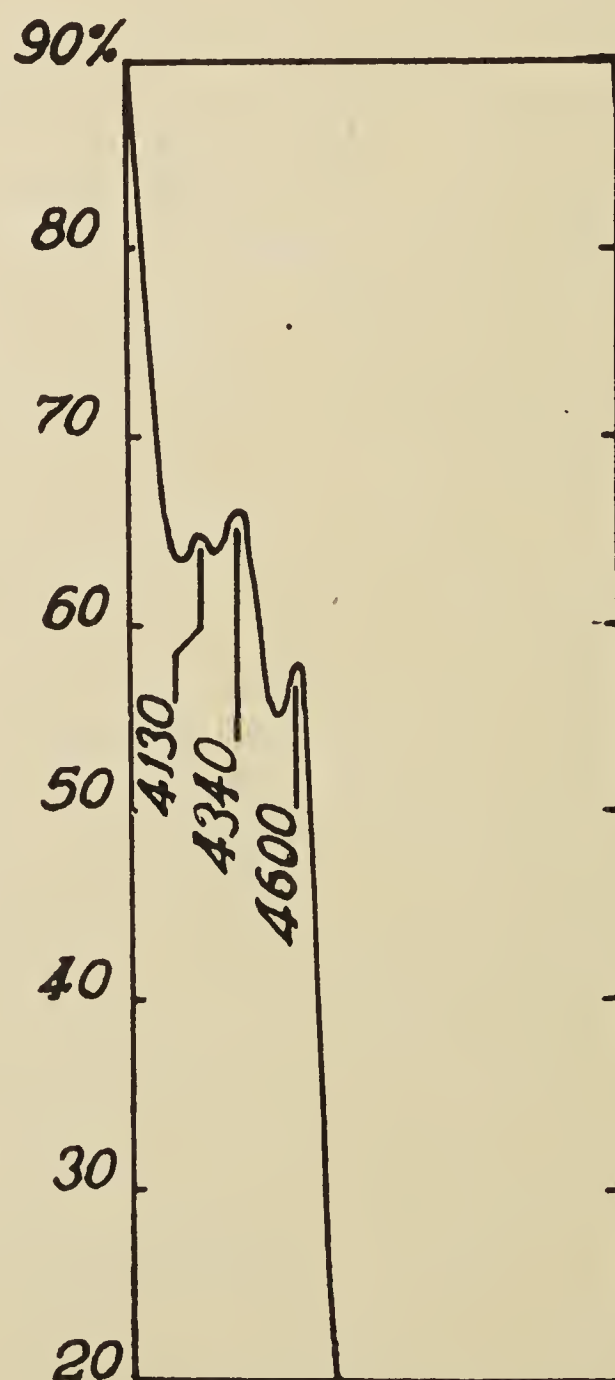


Figure 2. Absorption spectrum of yellow rose.

Figure 2 is the spectrophotometric record of the alcoholic extract from a yellow rose. The figures entered are wavelengths in Å. The absorption is manifested only in the blue region of the spectrum and the three peaks which appear in the record are an indication that the pigment which gives the characteristic golden-yellow colour to the extract belongs to the well-known class of organic compounds known as the carotenoids.

4. Explanation of the colour variations

The features noticed in the recorded curve of absorption appearing as figure 1 enable us to give a reasonable explanation of the great range of colours actually exhibited by roses. The factor which is different for the roses of different colour is the quantity of pigmentary material present in the petals. On the basis of such variation, it is possible to deduce the results to be expected and compare them with the actual facts of observation.

We may begin with the cases in which the pigment is present in minimal quantities. It is evident from figure 1 that in such cases, the absorption of light by the petals would be principally observed in the range of wavelength from 500 to 550 m μ and that it would be much less both at greater and smaller wavelengths, becoming altogether insensible as we approach the red end of the spectrum. Examination of pink roses held in bright light through a pocket spectroscope discloses just such a situation. Further, it is found that the deeper the pink colour of the rose, the greater is the absorption noticeable in the green sector of the spectrum between 500 and 550 m μ . But both the red and the blue regions of the spectrum persist.

We may next consider the cases in which the pigment is present in substantial quantities, sufficient to make the absorption by the petals completely effective except in the regions of the spectrum where the absorptive power is quite small. Referring again to figure 1, it will be seen that in such cases, the light which escapes such absorption could appear only at the extreme red end of the spectrum, and the rose would appear of a deep crimson colour. With less pigment available, wavelengths upto about 600 m μ could escape complete absorption and the colour of the rose would then be a bright red instead of a deep crimson. When the quantity of pigment available is still smaller, wavelengths between 570 and 600 m μ would commence to appear in the light diffused by the petals and the colour of the rose would alter from red to scarlet. With further diminution of the quantity of pigment available, the light diffused by the petals would extend further towards still shorter wavelengths and the colour of the rose would alter from scarlet to orange. Actually, when orange roses are viewed through a pocket spectroscope, we find that the spectrum from the extreme red upto 550 m μ comes through, while shorter wavelengths are absorbed. In all these cases, the blue region of the spectrum is scarcely to be seen.

The author has not had an opportunity of examining roses which have been described as exhibiting purplish hues. If blue roses were ever forthcoming, they would assuredly exhibit the spectrum of florachrome A, with its characteristic bands of absorption in the red, yellow and green regions.

The spectrophotometer records reproduced above were made in the Instruments Laboratory of the Indian Institute of Science, to the authorities of which the author's thanks are due.

Spectrophotometry of floral extracts

SIR C V RAMAN

ABSTRACT

Spectrophotometer records of the absorption spectra of the acetone extracts of the pigments of four flowers, respectively red, purple, blue and yellow in colour, are reproduced with appropriate comments on the features which they exhibit.

1. Introduction

Many flowers which present attractive colours exhibit an intense absorption over extensive regions in the spectrum. It is not easy in such cases to determine by simple observations *in vivo* the nature of the pigmentary materials responsible for the observed colours. The extraction of the pigment from the petals by appropriate solvents, e.g., acetone, followed by spectrophotometric examination of the extract diluted to such extent as may be found necessary is very helpful in such cases. Likewise, a similar procedure may be followed with advantage in the case of flowers exhibiting very delicate colours, the spectral character of which is not easily acceptable to direct observation. Extended studies of this kind with many flowers should be of help for a fuller understanding of the origins of floral colour in general. The present communication reports the results obtained in a few typical cases of this nature.

2. *Hibiscus rosa sinensis*

This is a widespreading shrub, 5–8 feet high with bright shining thick foliage. It is constantly in bloom with large brilliant scarlet-red flowers which have pretty columns of pistil and stamens projecting from their centres. The shrub with its flowers has an attractive appearance as seen from a distance and hence is very effective as an ornamental hedge. Viewed through a direct-vision spectroscope, the flowers exhibit wavelengths greater than $600\text{ m}\mu$ in full strength, while shorter wavelengths suffer a practically complete extinction. Immersion of the petals in acetone results in a rapid extraction of the colour. Viewed through a spectroscope, a 5 cm column of the extract exhibits visible absorption bands in the

yellow and green sectors followed by a strong general absorption in the blue region. Figure 1 is a spectrophotometer record obtained with an absorption cell 2 cm thick. The numbers entered in the figure are the wavelengths in Å units. It will be seen that apart from the three absorption bands in the yellow, green and blue-green characteristic of florachrome B, two other bands are noticeable in the blue and violet regions of the spectrum. It may be inferred from this that besides florachrome B which is responsible for the red colour, there is also present a yellow pigment which has a strong absorption in the short-wave region of the spectrum. This inference receives support from the fact that the colour of the acetone extract does not fade away completely after 24 h as in the case of the extracts from red or crimson roses but exhibits a residual yellow. It should, no doubt, be possible to separate the red and yellow pigments by chromatographic methods.

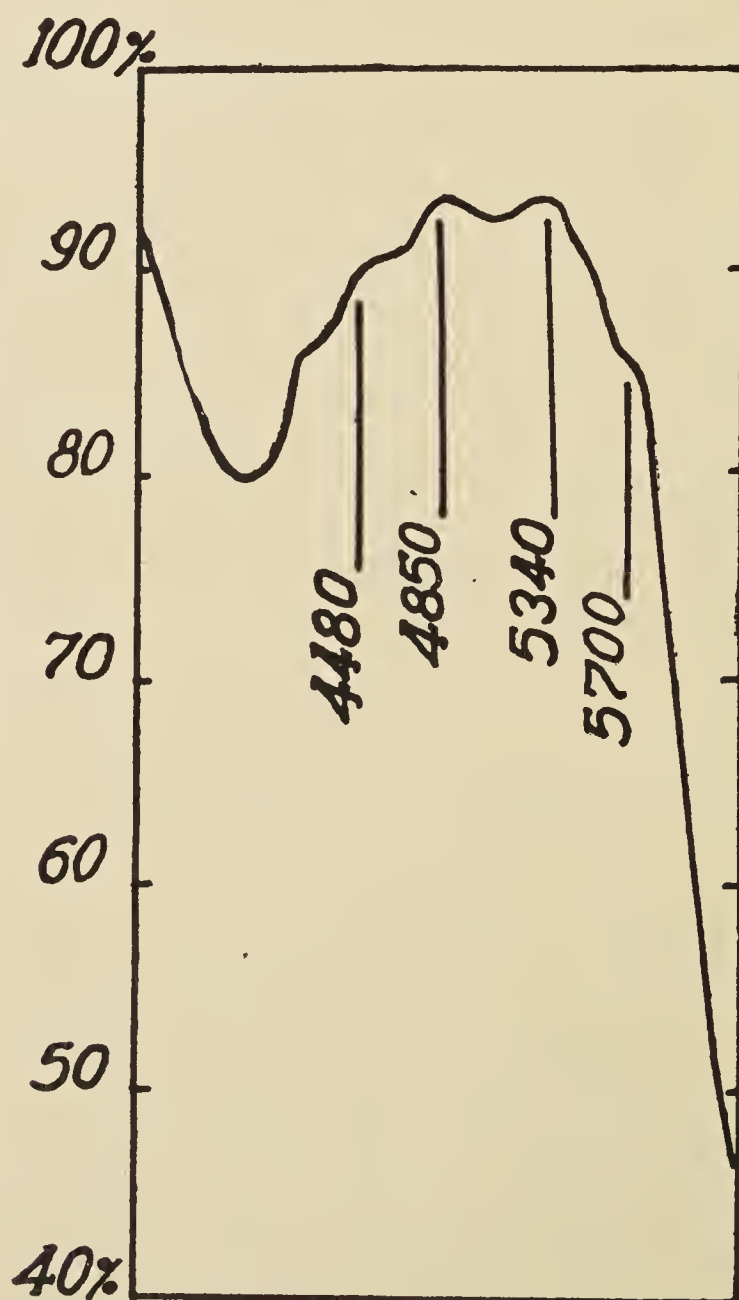


Figure 1. Absorption spectrum of the red *Hibiscus*.

3. *Lagerstroemia indica purpurea*

This shrub belongs to the botanical class *Lythraceae* and is popularly known as a crape myrtle. It is a deciduous shrub 6–10 feet high with small leaves and is very pretty in bloom with soft, fringed, showy flowers arranged in long erect sprays. The colour is readily extracted from the material by immersion in acetone. The spectrophotometric record of absorption by a cm column of the acetone extract is reproduced as figure 2.

The record shows some similarity to that of the acetone extract from the reddish-purple ground-orchid, *Spathoglottis plicata*, which *in vivo*, exhibits the typical spectrum of florachrome B with absorption bands appearing conspicuously in the yellow, green and green-blue regions of the spectrum.

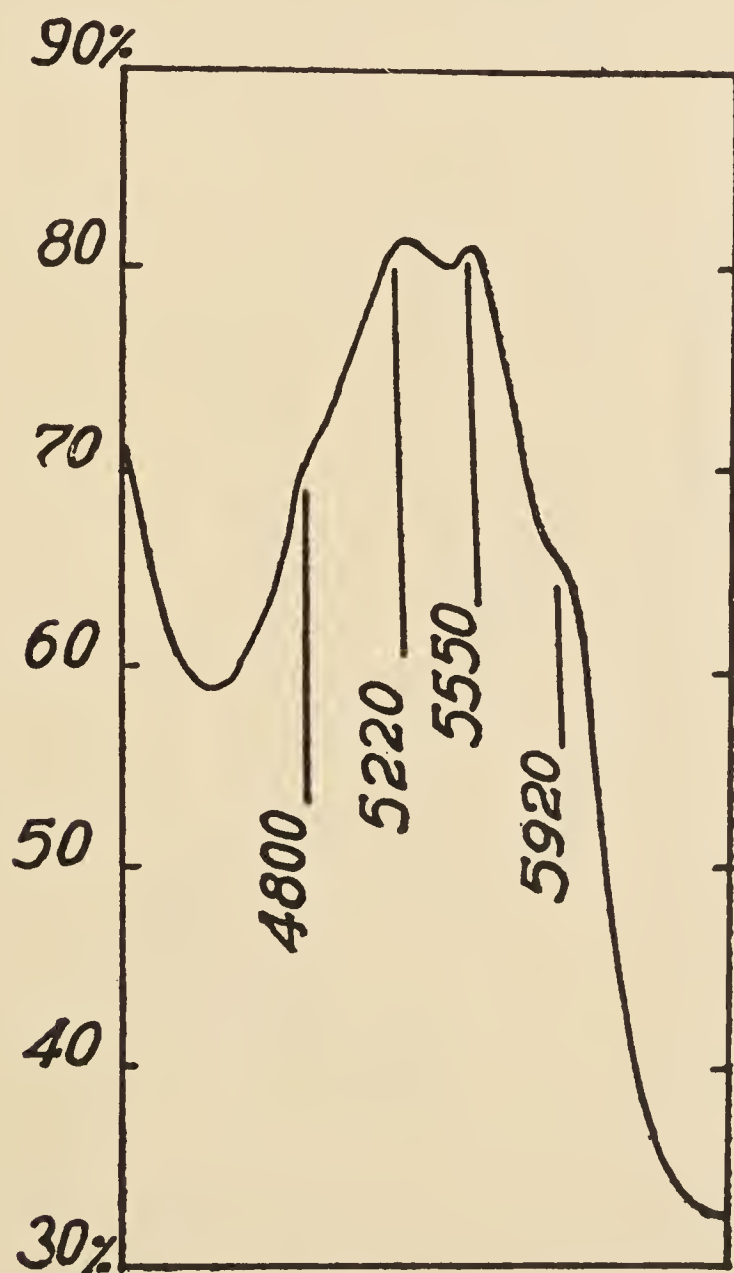


Figure 2. Absorption spectrum of the purple *Lagerstroemia*.

4. *Jacquemontia violacea*

This belongs to the botanical order *Convolvulaceae*, and is a small very free-blooming creeper with small cordate leaves. The flowers are also small and bell-shaped. They are blue in colour and are borne plentifully in all seasons. Hence, the creeper is sometimes referred to as *Ipomea semperflorens*. The colour may be extracted by grinding a sufficient number of the petals with acetone in an agate mortar.

Examined *in vivo*, the flower shows quite conspicuously the absorption bands in the yellow and in the orange-red regions in the spectrum which are responsible for the blue colour which it exhibits. A 5 cm column of the acetone extract exhibits a purplish-blue colour which is spectroscopically revealed as due to a conspicuous absorption-band covering the yellow region of the spectrum, a less conspicuous diffuse band in the red and a general weakening of the green region of the spectrum. The blue region in the spectrum is transmitted with fair strength. These features are recognisable in the spectrophotometer record of the absorption by a cm column of the acetone extract reproduced as figure 3. The spectral behaviour of the flower thus definitely belongs to the class florachrome A.

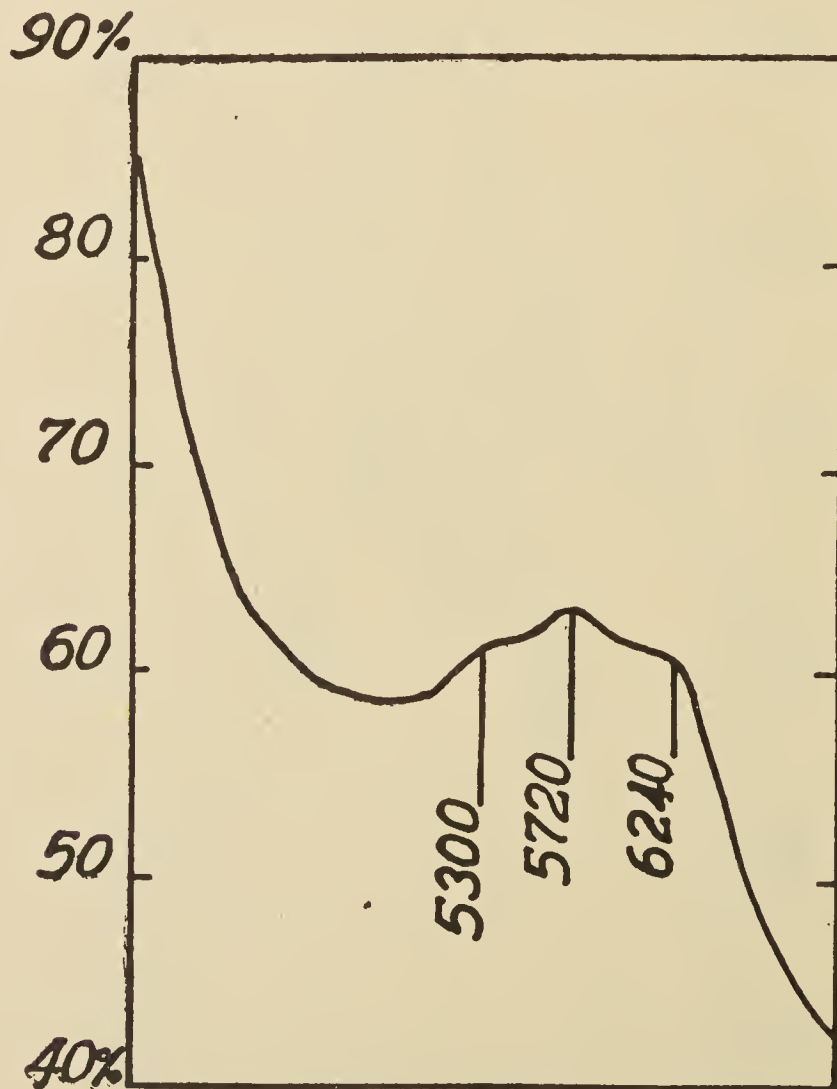


Figure 3. Absorption spectrum of the blue *Jacquemontia*.

5. *Tecoma stans*

This is a large shrub belonging to the botanical class *Bignoniaceae*. It is a very hardy quick grower attaining a height of about 10 feet. The foliage is handsome, consisting of graceful pinnate leaves. The shrub is commonly planted for screening compound walls or as hedging. The flowers are golden-yellow in colour, large, funnel-shaped and widely expanded and appear as clusters in terminal branches. The colour is readily extracted from them by immersion in acetone. Examined *in vivo*, the flowers exhibit a practically complete extinction of the shorter wavelengths in the spectrum upto about $510\text{ m}\mu$, while the rest of the spectrum appears in full strength. The acetone extract exhibits the same spectroscopic behaviour. Figure 4 reproduces a spectrophotometer record of the

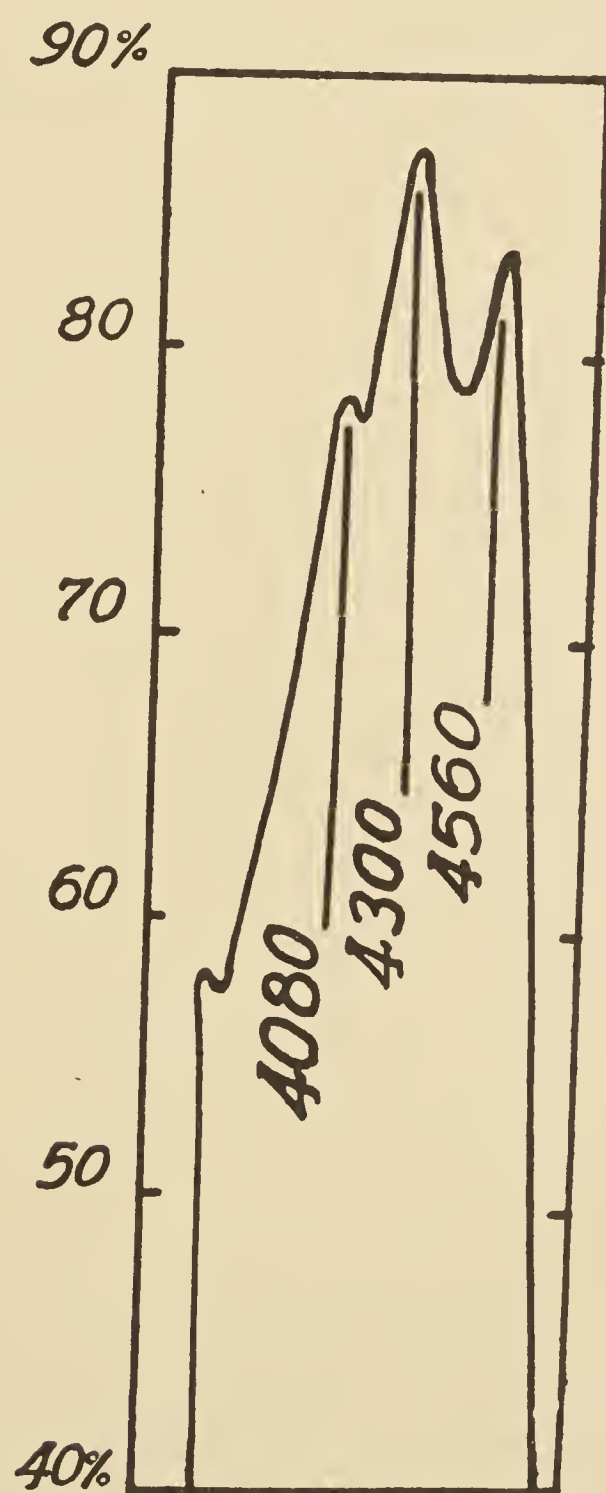


Figure 4. Absorption spectrum of the yellow *Tecoma*.

diluted extract. It shows three bands in the blue-violet region of the spectrum, indicating that the pigment may be identified as a carotenoid.

The records reproduced above were made in the Instruments Section of the Indian Institute of Science, to the authorities of which institution, the thanks of the author are due.

Blue delphiniums and the purple bignonia

SIR C V RAMAN

ABSTRACT

The spectroscopic behaviours of two flowers are described and discussed, illustrating respectively the optical properties of florachromes A and B.

The present article is intended to supplement the studies published in recent issues of *Current Science* on the nature and origin of floral colours. It deals with two flowers which exhibit vivid colours but which are totally different. The observations make it evident that in one of them, the colours arise from the presence of florachrome A and in the other they are ascribable to the presence of florachrome B.

Delphinium belladonna is a perennial bloomer of great beauty. Its flowers appear arranged on vertical spikes, each spike carrying several flowers. If the central spike is cut off as soon as it has finished flowering, the side shoots will flower. The material thus remains available for study for a considerable period. As the petals are not very thick, the most satisfactory procedure for observing their spectroscopic behaviour is to hold two of them together and view them against a strong light. The spectrum of the transmitted light exhibits three dark bands, the first of which centred at $630\text{ m}\mu$ is the strongest: the second at $580\text{ m}\mu$ is also well pronounced but not completely dark. The third band at $540\text{ m}\mu$ is also visible but it is much feebler than the others. Under the small dispersion provided by the viewing spectroscope, the visible spectrum presents the appearance of *three bright bands*, which are respectively red, orange-yellow and green separated by the dark absorption bands in the positions stated above. The wavelengths beyond $500\text{ m}\mu$ come through quite freely. The spectrum is thus characteristic of florachrome A, and is observed with all blue flowers.

Bignonia magnifica is a large bushy shrub which grows vigorously and bears flowers in great profusion. The flowers are of considerable size, and as each individual bush or plant can at any time carry a great number of them, it presents a magnificent sight. The colour of the flowers is a reddish-purple which is richest when the flower has just opened to its full extent. Later, the colour fades noticeably. The most satisfactory way of examining its spectroscopic behaviour is to hold two petals of the freshly opened flower together and examine light from a strong source which has passed through the pair. It will then be seen that the wavelengths greater than $600\text{ m}\mu$ and also the wavelengths less than $500\text{ m}\mu$ come

through freely. But the region from 560 to 600 $m\mu$ is strongly absorbed and the region from 500 to 560 $m\mu$ also appears much reduced in intensity. At high levels of illumination, the wavelengths between 560 and 600 $m\mu$ which include the yellow sector are the brightest part of the spectrum. *Bignonia magnifica* thus provides an excellent illustration of the role played by the yellow sector in the perception of colour, and especially of the fact that its exclusion from the spectrum results in the production of the purple sensation. It is also evident from the observations that the floral pigment functioning in *Bignonia magnifica* is florachrome B, since the characteristic absorptions of this florachrome appear in the yellow and green sectors of the spectrum leaving the red sector entirely unaffected.

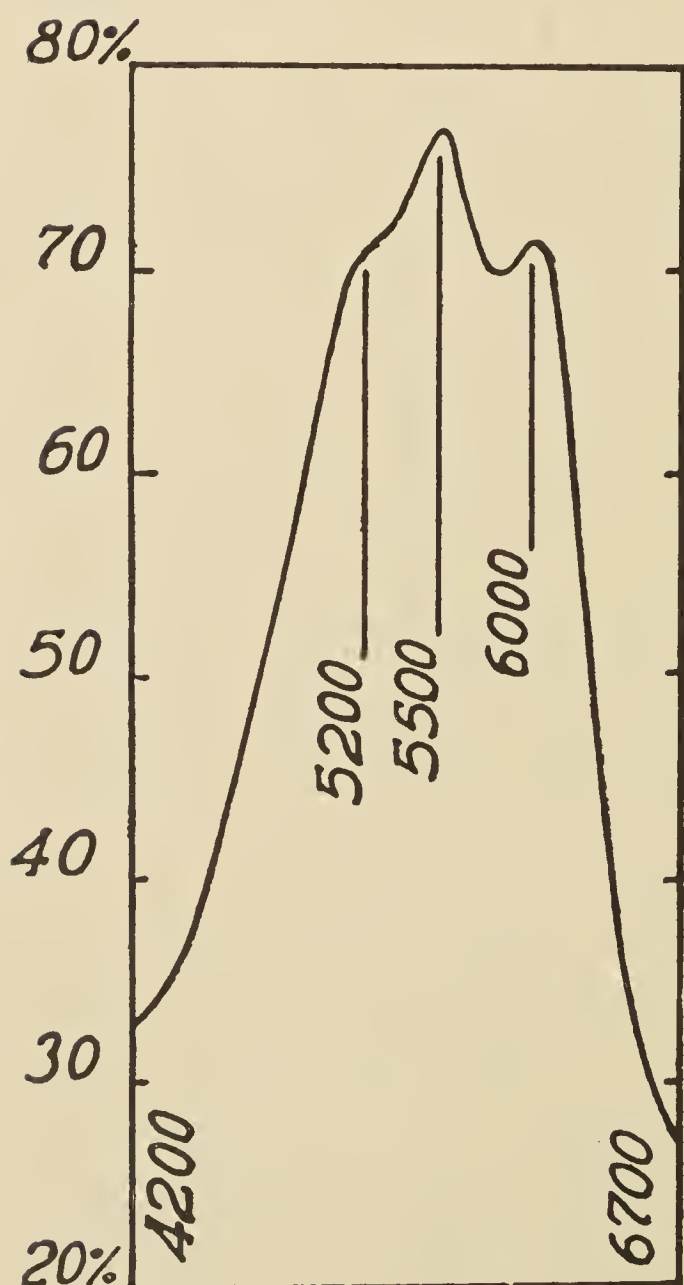


Figure 1. Absorption by delphinium extract.

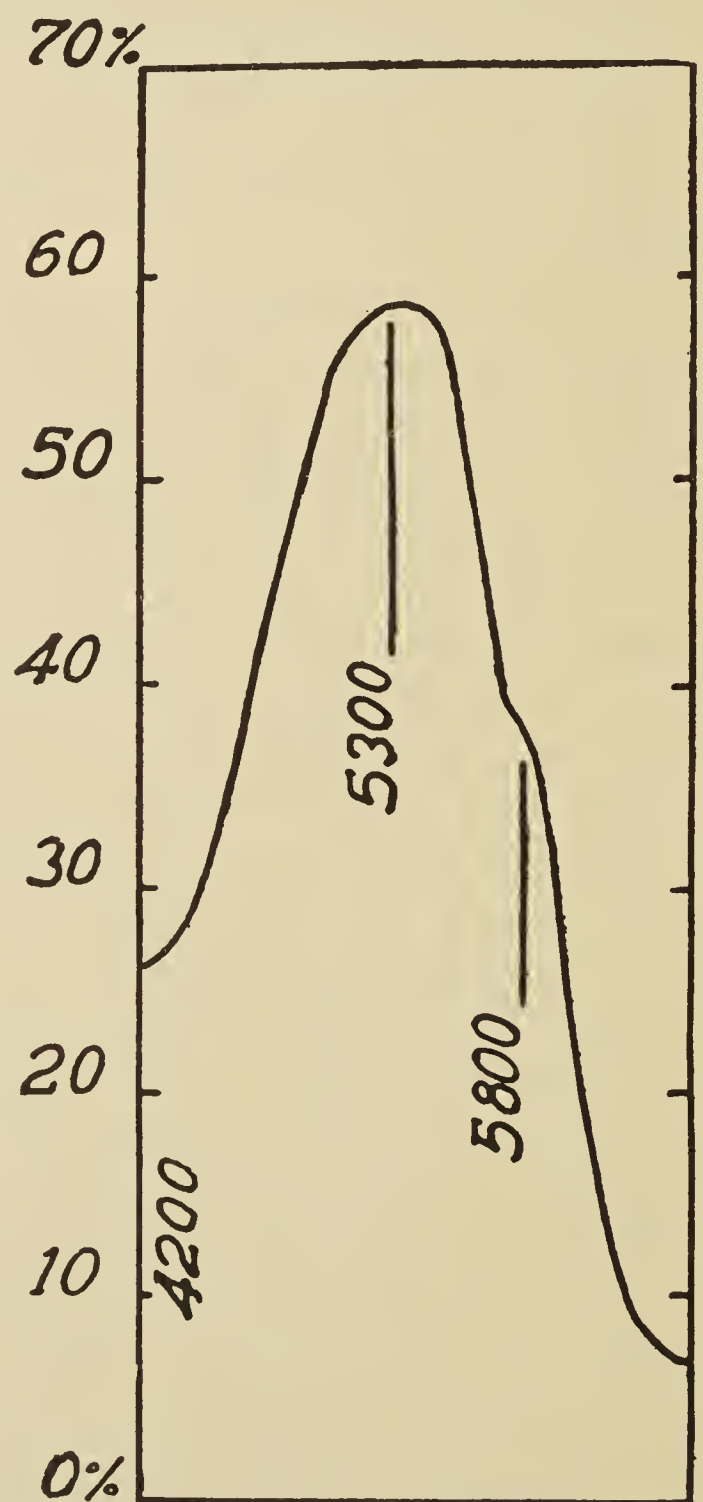


Figure 2. Absorption by bignonia extract.

Extraction of the floral pigments: Immersing the flowers of delphinium in either water or acetone produces no observable effect. It is necessary to grind the petals to a fine paste in an agate mortar using a small quantity of acetone as a lubricant. After pouring out the surplus acetone and squeezing out what is left, water is added to the paste which results from the grinding, and the mix is then stirred up and filtered through a cotton-wool plug. The result of these operations is a bright blue solution containing the material responsible for the colour of the flower. A spectrophotometric record of the absorption of light by this extract contained in a cell of 1 cm thickness is reproduced as figure 1.

The numbers shown in the figures are the wavelengths in Å units. The record exhibits a comparatively free transmission of the shorter wavelengths in the blue region of the spectrum, while the strong absorptions in the yellow and orange regions are responsible for the intense blue which is the colour actually perceived.

The colouring matter is readily extracted from the petals of *Bignonia magnifica* by the aid of acetone, with a little pressure in an agate mortar. The acetone extract is vividly coloured and a visual examination of the light transmitted through it through a spectroscope shows the absorption bands in the yellow and the green regions of the spectrum which are characteristic of florachrome B, while the blue and red sectors are freely transmitted. A spectrophotometric record of the absorption by the extract is reproduced as figure 2.

The spectrophotometric studies of the extracts were made in the Instruments Section of the Indian Institute of Science, to whose authorities the thanks of the author are due.

The varied colours of *Verbena*

SIR C V RAMAN

The garden *Verbenas* are very popular trailing plants of a perennial habit. They strike root as the shoots trail along the surface of the soil and meet with sufficient moisture. It is then possible to separate the rooted portions of the shoots from the parent and grow them independently. *Verbenas* are very serviceable as ground cover in shrubberies, for hanging baskets, for rockeries, for growing in beds and for pot culture. There are several species or varieties which have received distinctive names, viz., amongst which mentioned *Verbena hybrida*, *Verbena erinoides* and *Verbena peruviana*. The flowers of *Verbena* are produced in great profusion. They stand up well above the foliage in large velvety clusters of elegant shape. *Verbena erinoides* is also known as the Moss *Verbena* as the plants cover the ground completely.

Books on gardening stress the wide range of colours exhibited by the *Verbenas*. In one book, we find illustrations of a cluster of intensely blue flowers of *Verbena hybrida* and of a cluster of brilliant scarlet flowers of *Verbena peruviana*. The author of another book goes so far as to say that “there are very few flowers which can beat the *Verbena hybrida* in the exquisite range of colours, varying from white through blue and rose to purple and dark purplish-blue, with shades of pink and pale yellow”. It is evident, therefore, that *Verbenas* would be excellent material to illustrate the relationship between the observed colour and the spectroscopic behaviour of flowers.

Blue *Verbenas* would be of particular interest as they may be expected to display the spectral characteristics of florachrome A. At the time of writing, however, they were not to be seen in Bangalore. A purple species of *Verbena* is however quite common, and when as is frequently the case, it has been planted over an extensive area, the ground covered with the flowers presents the appearance of a carpet of that colour. Though the individual flowers are small, a cluster of them presents a substantial area, and its spectral character may be readily determined by viewing the cluster through a pocket spectroscope. An absorption band covering the yellow region of the spectrum is a striking feature, while the green region is visible and by comparison appears fairly strong. The red and blue regions of the spectrum are seen with apparently undiminished strength. The colouring matter of the purple *Verbena* is readily extracted by immersing the flowers in acetone. A spectrophotometric record obtained with a cell of 1 cm thickness containing the extract is reproduced as figure 1. The record exhibits three peaks of absorption, one of which appears in the yellow region of the spectrum and the other two respectively in the green and the green-blue regions. These spectral characteristics

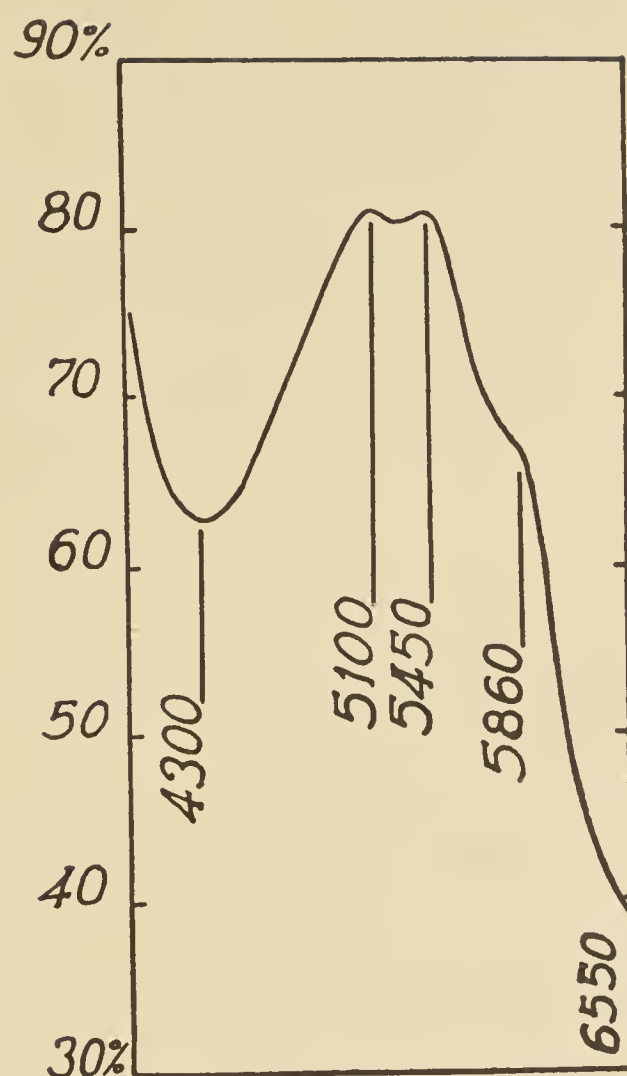


Figure 1. Absorption spectrum of acetone extract from purple *Verbena*.

may be identified as those of florachrome B. The purple *Verbena* furnishes an excellent example of the role that the absorption of the yellow plays in the perception of a purple hue.

In the author's garden at his Institute in Bangalore, a variety of *Verbena* is to be seen, the colour of the flowers of which may be described in general terms as being red. But it is highly variable, varying from a deep purplish-red to quite a pale pink. These differences appear partly to be due to a gradual fading away of the individual flowers, since those nearer the centre of the cluster which are the latest to open have the deepest colour, while the outermost are the palest. Spectroscopic examination of the individual flowers in a cluster reveals that the absorption appearing in the spectral region between 500 and 600 $m\mu$ which is responsible for the observed colour is very weak in the flowers which appear a pale pink, and is almost complete in those which exhibit a brilliant colour. The relative intensity of the absorption appearing in the green sector from 500 to 560 $m\mu$ and in the yellow sector from 560 to 600 $m\mu$ is also highly variable. The observed colour appears to be most saturated when the yellow sector is completely absorbed. This is indeed a general feature in all floral colours.

The spectrophotometer record reproduced above was made in the Instruments Section of the Indian Institute of Science to the authorities of which the author's thanks are due.

The pelargoniums

SIR C V RAMAN

ABSTRACT

The spectra exhibited *in vivo* by pelargoniums of various colours, as also the absorption spectra of their acetone extracts have been studied. The colouring material is the same in all cases, but it is present in widely different quantities.

Brilliantly coloured flowers appearing in clusters at the end of terminal stalks,—and there may be a dozen or more such clusters carried by one plant—make the pelargonium a great favourite with gardeners. The individual plant being itself of no great height or spread, it can be conveniently grown in pots of modest size. Pelargoniums are to be found in extensive use as window-box plants for town houses in the cooler climates of the world. These plants (which are commonly called geraniums) do not thrive well in the hot plains of India, but the climate of Bangalore appears to suit them excellently. A hundred pots disposed at regular intervals along the boundary of a garden and kept in condition make a magnificent display of colour. The pots should be raised above the ground by placing them on bricks to prevent entry of larvae coming up from the earth.

There are several distinct species of pelargonium which may be readily distinguished from each other by the shape and feel of the leaves. *Pelargonium inquinans* has leaves which are almost circular, soft to the touch and have undulating edges. *Pelargonium peltatum*, also known as ivy-leaved geranium, has trailing slender stems, and polished, thick, dark green leaves. The pelargoniums seen at Bangalore fall into five colour groups. The ivy-leaved plants bear flowers which are a rich red, approaching crimson. The soft-leaved species usually exhibit flowers of a brilliant scarlet colour. There are also plants bearing numerous clusters of flowers which are a bright rose-pink and others with flowers of an orange hue. Some plants are also to be seen with flowers which are basically white but have red margins. The delightful scent of the leaves of some geraniums also deserves mention.

Viewing a cluster of the flowers held in sunlight through a pocket spectroscope reveals the progressive change in the character of the spectrum as we pass from the case of the red flowers to the scarlet and then to the orange. With the red flowers, there is a practically complete extinction of all wavelengths less than $600\text{ m}\mu$ in the light which emerges from the petals after internal absorption and

diffusion. The limit shifts to $580\text{ m}\mu$ in the case of the scarlet flowers and to $550\text{ m}\mu$ for those which are orange. On the other hand, the flowers which are a bright rose-pink in colour do not exhibit a complete extinction of any part of the spectrum. There is a marked weakening of the spectrum in the wavelength range from 500 to $600\text{ m}\mu$ which includes the green and yellow sectors, but there is no observable absorption in the region of wavelengths greater than $600\text{ m}\mu$. Wavelengths less than $500\text{ m}\mu$, in other words, the blue regions of the spectrum, remain visible though with appreciably reduced intensity. The situation is thus very similar to that observed with roses of different colours and discussed in a recent issue of *Current Science*.

The red flowers of the ivy-leaved pelargonium readily yield up their colour when placed in a glass beaker and shaken up with sufficient acetone to cover the petals. The acetone extract shows at first the same red colour as the flowers themselves. But the colour of the extract fades away rapidly in the course of a few minutes and soon disappears completely. The progressive fall in absorption can be followed with a 5 cm column of the extract held against a brilliant field of white light and viewed through a spectroscope. The absorption which at first is complete for all wavelengths less than $600\text{ m}\mu$ is observed to diminish over the whole range, and especially in the region between 550 and $600\text{ m}\mu$ which is normally the brightest part of the spectrum. Wavelengths less than $500\text{ m}\mu$ begin to make their appearance and progressively become more intense. Finally, the entire spectrum comes through with no observable weakening.

Acetone extracts may also be obtained with the flowers of other hues and the progressive falling off in colour and absorptive power may similarly be followed. But the effects are much less striking than in the case of the red flowers.

Since, in all cases, the absorption by the flowers of pelargonium appears in the yellow and the green sectors of the spectrum, we are justified in recognising the material responsible for the observed colour as florachrome B. It is also evident that the colour variations observed are due essentially to the quantity of the pigment present in the petals being substantially different in the different cases.

The red oleander and the purple petrea

SIR C V RAMAN

The oleanders, known botanically as *Nerium* and classed in the group *Apocynaceae*, are flowering shrubs which no Indian garden is without. They are graceful, large, spreading bushes growing to a height of three metres or more, with a number of cane-like stems starting from the ground and bearing narrow evergreen, lanceolate leaves. The shrubs grow to perfection in sunny situations and in sandy or stony soils. The flowers are produced very freely throughout the year in great profusion in large terminal clusters. There are several varieties, with single or double flowers, which may be pure white, or exhibit colours ranging from pink to a deep red or crimson.

Viewing the red oleander held in a bright light through a pocket spectroscope and comparing the spectrum with that of the light diffused by a sheet of white paper, it is seen that the wavelengths greater than $600\text{ m}\mu$ do not suffer any loss of intensity. There is a very marked absorption of the region of wavelengths between 500 and $600\text{ m}\mu$, in other words of the green and yellow sectors of the spectrum. Wavelengths less than $500\text{ m}\mu$ continue to be visible, though with noticeably reduced intensity. The colour is readily extracted from the flower petals by immersing them in acetone, followed by vigorous shaking. Placing the acetone extract in a five-centimetre long column, and viewing a bright source of light through it, the absorption spectrum exhibits the features which may be expected to be observed in these circumstances. A maximum of absorption in the green is clearly seen as a darker band at about $540\text{ m}\mu$, superposed on a general absorption extending on either side of it. This covers the yellow of the spectrum upto $600\text{ m}\mu$, beyond which the red region is seen with undiminished intensity.

A spectrophotometric record of the absorption by a rather dilute acetone extract from a red oleander is reproduced as figure 1. Three features marked with the respective wavelengths in Å units, viz., 5010, 5320 and 5620 are seen in the record. These appear in the same positions as those observed in the acetone extract from a red rose reproduced as figure 1 on page 504 of the issue of *Current Science* for November 5, 1969. It is evident that the origin of the red colour of the oleander is the same as that of red rose, viz., the presence of florachrome B in the petals of the flower in each case.

Petrea volubilis belongs to the botanical order *Verbenaceae*. It is a shrub which can be described as a woody vine with a grey bark and characterised by stiff and rough leaves of some size. Being a strong climber, the plant will attain great height

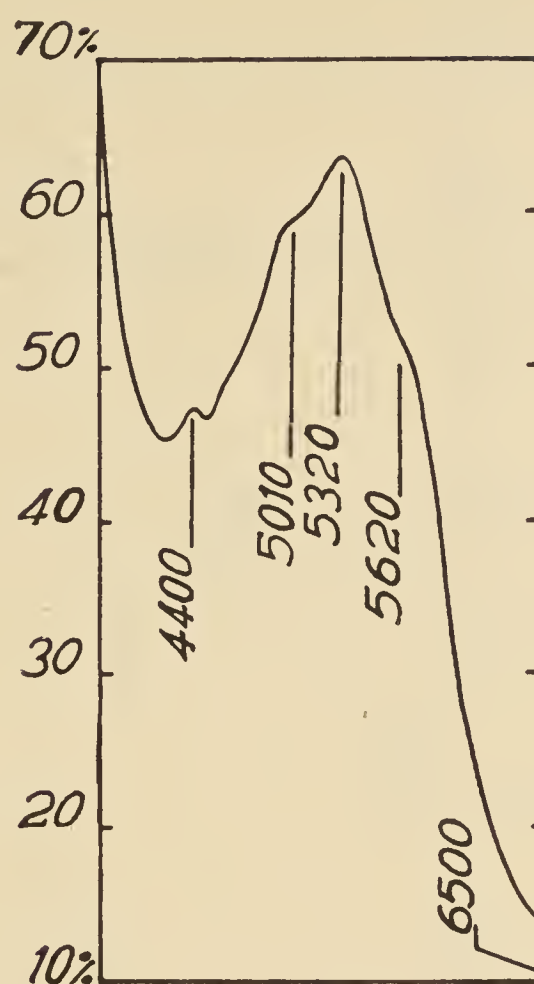


Figure 1. Absorption by acetone extract of red oleander.

and cover a considerable area if left unpruned. It bears bluish-purple five-petalled stars in long elegant wreath-like sprays and hence has been given the popular name of purple wreath. Racemes of these stars, some 15 or 20 cm in length, crowd the plant in the flowering seasons, covering it up in a mass of colour. Given a support of adequate size on which it can climb and establish itself, the plant then makes an impressive show. The five-petalled stars which might be mistaken as flowers are actually only the calices which remain after the true flowers have fallen off. The latter are much smaller and have five petals of a deeper colour. They may be seen resting in two or three of the end calices. One of the five petals in each flower carries a white splash in the middle.

Examined *in vivo* through a pocket spectroscope, the five-petalled stars exhibit a spectrum in which the most noticeable feature is the nearly complete extinction of the yellow region of the spectrum, accompanied by a noticeable reduction of the intensity of the green sector. The blue region of the spectrum, on the other hand, appears without any great diminution of brightness. The red end of the spectrum is also seen with nearly its normal intensity. On account of their small size, the spectroscopic examination *in vivo* of the true flowers is somewhat difficult. But they appear to exhibit the same features as the calices, but in a more accentuated degree.

The material which is responsible for the colour exhibited by the calices of *Petrea volubilis* is readily extracted by shaking them in a glass-beaker with

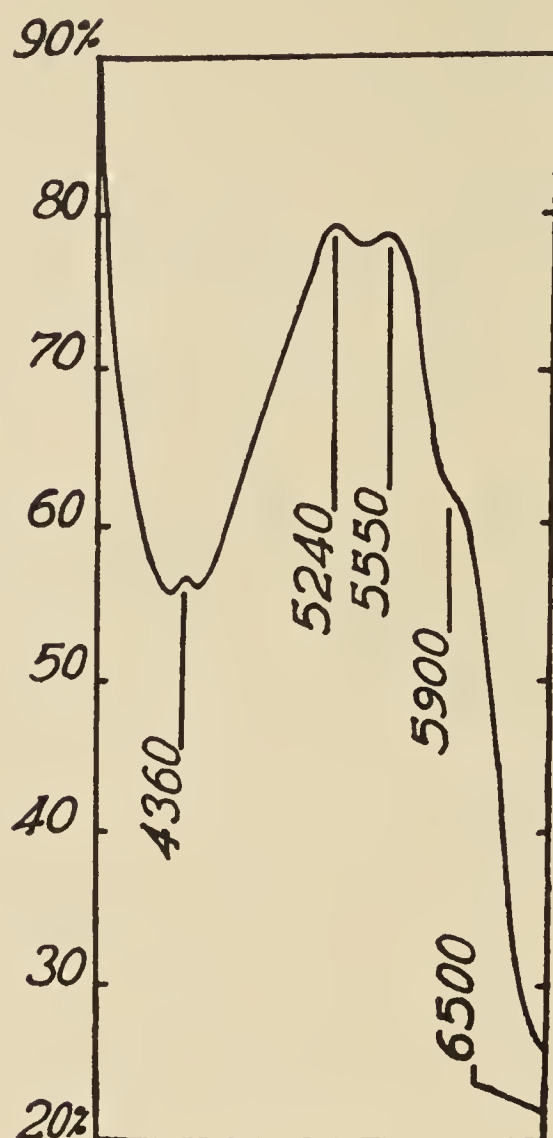


Figure 2. Absorption by acetone extract of purple petrea.

acetone. The absorption spectrum exhibited by a column of the extract of 1 cm depth is reproduced as figure 2. It exhibits features which are very similar to those observed in the spectrophotometer records obtained with the acetone extracts of the purple flowers of *Lagerstroemia indica* and of the purple verbena, which were reproduced in earlier issues of *Current Science*. These records illustrate the immensely important role played by the yellow sector of the visible spectrum in the perception of light and colour. The absorbing material may be identified as florachrome B, with a possible admixture of florachrome A. The presence of the latter would serve to intensify the bluish-purple colour actually observed.

THE PHYSIOLOGY OF VISION

SIR C V RAMAN



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CHAPTER I

Introduction

The nature and properties of light and its interactions with material bodies obviously play a fundamental role in the functioning of our visual organs. A clear understanding of the physical constitution of light and of the phenomena resulting from its incidence on the visual organs is therefore essential for any valid interpretation of our visual sensations. It is precisely in these respects that the excursions into the field of visual physiology made in the nineteenth century were at fault. As is well known, light was regarded in the nineteenth century as a form of energy which propagates itself as wave-motion, and is distributed through space in a continuous manner. Its interactions with material bodies were also interpreted on the same basis. Present-day ideas regarding these matters are, of course, altogether different. There is therefore no reason to believe that the ideas regarding the nature of vision and of visual processes inherited from the nineteenth century would be sustainable at the present time, either on theoretical grounds or even as purely empirical descriptions or interpretations of the observed phenomena.

Two beliefs or hypotheses handed down from the nineteenth century figure prominently in the literature of the physiology of vision. The first is the trichromatic hypothesis usually associated with names of Thomas Young and Hermann von Helmholtz. The other is the duplicity theory of vision which postulates that there are two distinct kinds of vision, known as photopic vision and as scotopic vision which function respectively at the higher and at the lower levels of luminosity, photopic vision enabling us to perceive both light and colour, and scotopic vision only light but no colour. Of more recent origin is the so-called photo-chemical theory of vision which has received a measure of acceptance from several authors but has not escaped criticism by others.

The purpose of the present volume is to set out in a systematic manner the methods and results of the experimental investigations on diverse aspects of vision carried out by the author during recent years. The aim of the studies was to obtain an insight into the subject by independent study without being influenced by ideas and beliefs inherited from the past. It has emerged from the author's studies that none of the notions referred to in the preceding paragraph is reconcilable with the actual facts of the case. The studies have led to a new picture of the nature of vision and new interpretations of our visual experiences. These have been described in detail and discussed in the chapters which follow.

CHAPTER II

Waves and corpuscles

The phenomena which light presents to us for study fall into two groups. The first class of phenomena comprises those which can be described or explained on the assumption that light is a species of wave-motion in space which possesses a great velocity and other characteristics related to its propagation. In the second class of phenomena, we are concerned with light as a form of energy which is emitted or absorbed or scattered by material substances and which changes its form as the result of its incidence on such substances. In all cases of this kind, it becomes necessary to recognise the corpuscular nature of light, in other words to assume that it consists of discrete units of energy of which the magnitude is related to the frequency of wave-motion as recognised in the first class of phenomena by the simple relation $\varepsilon = h\nu$. Here ε is the energy of the corpuscle, ν is the frequency and h is Planck's constant of action. These two descriptions of the nature of light are mutually complementary. In other words, they refer to two distinct and non-overlapping sets of cases. But both descriptions have to be accepted to enable us to obtain a complete picture of the nature and behaviour of light.

Wave-optics includes within itself the entire body of theory and practice known as geometrical optics. This concerns itself with the functioning of optical instruments, treated on the basic assumptions of the rectilinear propagation of light and that the media traversed by light possess known refractive indices and dispersive powers. But the wave-like characters of light are most clearly manifested in the class of phenomena designated as interference and diffraction. In these phenomena, the periodic nature of wave-motion and its relation to the wavelength come directly within the reach of observation. The length λ of the waves as thus determined is connected with their frequency ν and their velocity c in the medium by the simple relation $\lambda = c/\nu$. The cases in which λ has a definite value and hence the frequency ν and the energy $h\nu$ of the light corpuscle are precisely known are of special importance. The light which can thus be specified appears as a single sharp line in the spectrum of the radiation as exhibited by a prismatic spectrograph or by a diffraction grating. It is then referred to as monochromatic light and it is composed of corpuscles all having the same energy. If, on the other hand, the spectrum as exhibited by such instruments is a continuous band of light, the wavelength λ and hence the frequency ν and the corpuscular energy $h\nu$ show corresponding ranges of variation.

From what has been said above, it follows that the formation of optical images

by the dioptric media of our eyes on their retinae falls within the scope of wave-optics. But, on the other hand, the actual perception of such light following its incidence on the retinae lies entirely outside its scope. For, the perception of light involves the absorption of the incident light as well as the transformation of its energy to a form that can be transmitted through the optic nerves to the centres of perception in the brain.

The role played by the corpuscular nature of light in its visual perception will occupy us in later chapters. It will be useful, however, to devote the rest of the present chapter to the consideration of the wave-optical properties of light. For, as we shall see later, the phenomena encountered in this field are helpful to us in the study and interpretation of our visual perceptions.

The simplest technique for exhibiting the interference of light is to lay one clean glass plate on another such plate and to view the air-film enclosed between the two plates by reflected light, making use of an extended source of light. The two streams of light reflected respectively at the two surfaces bounding the air-film reach the eyes practically in the same direction and with intensities which are nearly identical. But the optical paths traversed by them differ by twice the thickness of the air-film, if we assume that it is viewed in the direction of the normal to the surfaces. Interference then results either in the extinction of the reflected light or in a four-fold increase of its brightness according as the two streams of light are in opposite phases, or in agreement of phase. The varying thickness of the air-film then manifests itself as an alternation of dark and bright bands over its area, provided that the light employed has a definite wavelength, as is the case if, for example, the light of a sodium-vapour lamp is used for the observations. The two nearly coincident yellow lines in the spectrum of the lamp then give us the needed "monochromatic" light.

Photographs of two interference patterns of this kind recorded with the yellow light of a sodium lamp are reproduced as figure 1(A) and (B) in plate I. In figure 1(A), the interferences appear as concentric circular rings around a central dark region where the two plates were in actual contact, the thickness of the air-film increasing rapidly as we proceed outwards from this centre. In figure 1(B), the fringes appear as a series of approximately parallel bands, commencing from the region where the plates (which were both optical flats) had been forced into contact and the air-film between the plates is thus a wedge of small angle. As already stated, the fringes were in each case observed and photographed with monochromatic light, and the interferences are therefore seen at their best. In a later chapter, we shall describe and discuss the phenomena observed in such cases, when instead of the light of a sodium-vapour lamp, white light is employed for viewing the interferences.

A tungsten filament heated to a high temperature by the passage of an electric current emits a brilliant white light. Examined through a prismatic spectroscope, the emitted light appears as a continuous spectrum exhibiting the usual sequence of colours. The wavelength of the light in such a spectrum increases progressively

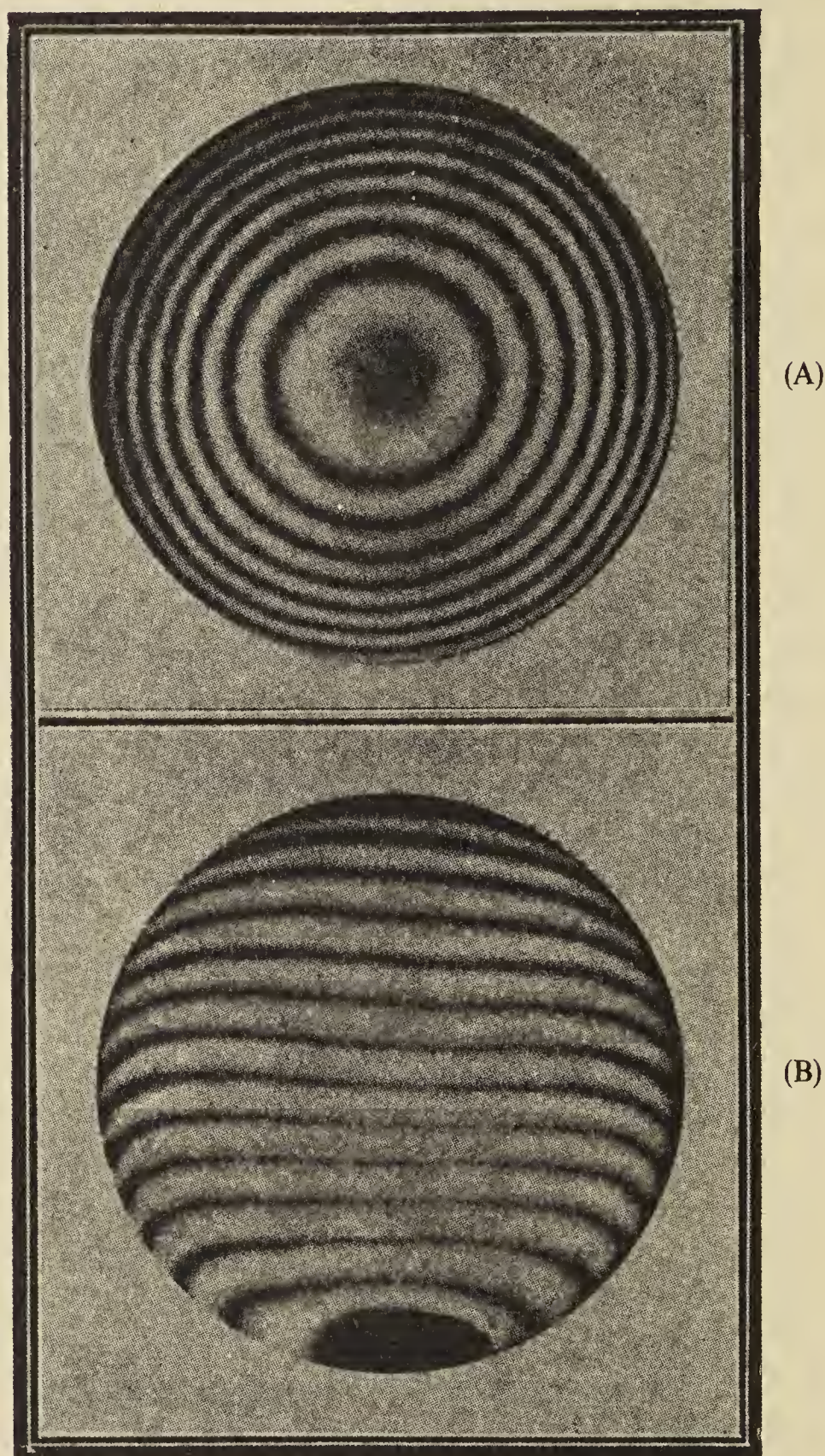


Figure 1. Interference patterns in sodium light.

Plate I

from one end to the other, from say 4000 Å units at the violet end to say 7000 Å units at the red end. The principle of interference may be utilized to exhibit this progression of wavelength to the observer's eye, the continuous spectrum being transformed into a succession of sharply-defined bands of progressively increasing wavelength. The technique needed to achieve this result is fairly simple. Two circular plates of optical glass are made use of. Their faces are ground flat and polished to a high degree of perfection. One face of each plate is half-silvered, and the two plates are held within a tubular support in such manner that the silvered faces are adjacent and parallel, their separation being a mm or less. The gap between them should be capable of being varied from zero upto the desired value, while their parallelism remains perfect. The use of suitable guides and a fine screw permits of this being achieved. The plates thus mounted are held normally before the slit of a spectroscope. White light from a small but brilliant source, e.g., a glowing tungsten-filament, passes normally through the plates and enters the slit of the spectroscope. The spectrum as seen through the eye-piece then exhibits a succession of bright lines on a dark field. The spacing of these lines can be varied by moving the two plates closer together or further apart as desired.

In a later chapter, we shall see that the technique here described can be used to study the progression of colour in the spectrum of white light and to estimate by simple inspection, the capacity of human vision to detect colour differences. An interesting feature of the technique is that the bands in the spectrum produced by it are equally spaced in respect of wave-number differences, in other words, the successive lines represent equal increments of the corpuscular energy of the light. This follows from the fact that the successive bands correspond to successive integral values of the number $2d/\lambda$, where d is the separation of the plates and λ is the wavelength of the light. Figure 2(A), (B), (C) in plate II reproduce the banded spectrum of the light of a tungsten lamp photographed in the manner described with three different separations of the plates in the interference apparatus. The number of bands into which the spectrum is channelled is 120, 60 and 30 while the wave-number separation between each band and the next is 72, 144 and 288 respectively in the three figures.

CHAPTER III

The structure and functioning of the retina

A role of outstanding importance in the functioning of the organs of vision is played by the retina, which is the sensitive screen at the back of the eye on which the picture of the world outside formed by its dioptric media falls. Indeed, it may be said that what the retina is capable of accomplishing determines what we can see and recognise in the objects under view. We shall concern ourselves in the present chapter with the methods of observation which enable us to view the living retina and thereby to gain some understanding of its structure and functioning.

The instrument referred to as the ophthalmoscope enables the interior of the eye to be illumined and to be viewed by another observer. What is known as the fundus of the eye then comes into view. The position of the details seen on it naturally depends on the direction in which the eye which is observed is orientated with respect to the illuminating beam. Pictures in colour of the appearance of the fundus are to be found reproduced in numerous treatises. Particularly striking are those which appear in Polyak's monumental treatise entitled *The Vertebrate Visual System* published by the Chicago University Press in the year 1957. We may here refer to figures 148, 165 and 363 which appear facing respectively pages 258, 280 and 606 of that work. These three pictures between them serve to give us a fairly complete idea of the structure of the retina, so far as the ophthalmoscope can reveal it.

It is a remarkable fact that the central part of the retina, in other words, the area which is made use of when we turn our eyes towards the objects which particularly interest us appears comparatively featureless as viewed through the ophthalmoscope. It is possible, however, to recognise a circular patch at its centre which appears different in colour or in brightness from its surroundings. At a considerable distance from this central region, and indeed almost on the periphery of the fundus, if the former appears at the middle of the picture, is seen the most conspicuous feature of the retina, viz., the region known as the optic papilla. This appears as a round disc. Surrounding it and emerging at various points inside the area, blood vessels are seen, both arteries and veins, traversing the retina. A feature particularly worthy of remark is that these larger blood-vessels curve round so as to avoid the central region of the retina. Blood-vessels of smaller diameters which take off from the larger vessels however traverse the retina and proceed towards the central area. But even these do not actually extend to or reach the central area.

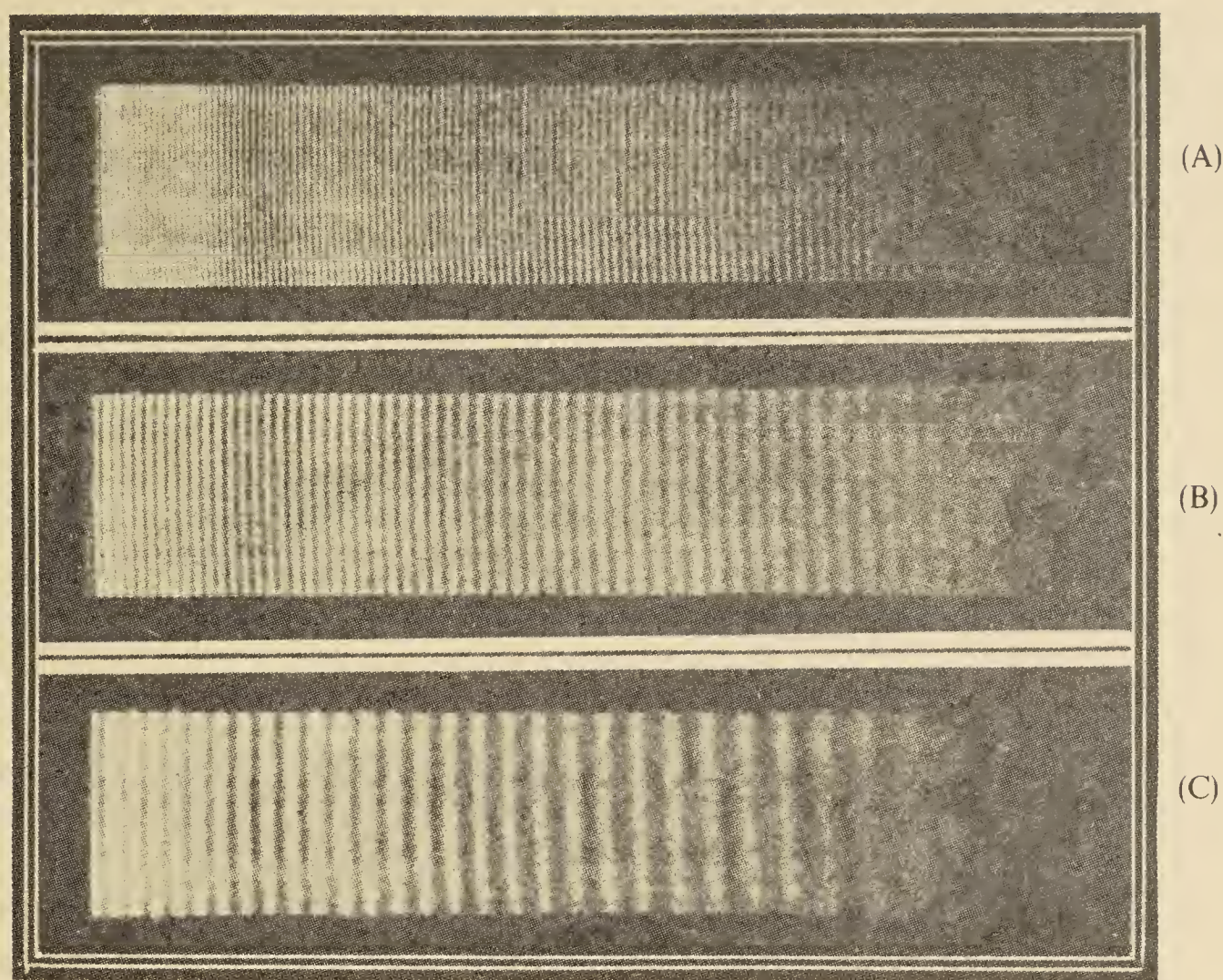


Figure 2. Channelled spectra of white light.

Plate II

The optic papilla is also the region towards which the nerve-fibres converge from various parts of the retina. Here they are bunched together and finally emerge as the optic nerve from the eye-ball towards the brain. This feature is well shown in figure 148 of Polyak's book and even better shown in figure 165 which is a picture of the fundus of a Nubian youth aged 17. Translucent bundles of optic nerve-fibres can be traced for a great distance beyond the disc of the optic papilla. Another noteworthy feature is that the nerve-fibres from other parts of the retina do not proceed across its central region but arch round it, both above and below, to avoid traversing it.

The avoidance of the central area of the retina by the larger blood-vessels, as also by the nerve-fibres streaming towards the optic papilla from other parts of the retina, is a feature which evidently favours the clear perception of the images of external objects falling on the central region. Apart from giving this indication, the ophthalmoscopic view does not really tell us very much about how the retina actually functions. Much less does it reveal the great differences in the activity of the retina over its different areas. These aspects of the structure and functioning of the retina are, however, exhibited in a most striking fashion when it is studied making use of a technique devised and perfected by the author which will presently be described.

The technique employed is the use of a colour filter which freely transmits light over the entire range of the visible spectrum except over a limited and well-defined region which it completely absorbs. It is possible by the use of suitable dye-stuffs in appropriate concentrations to prepare colour filters of gelatine films on glass exhibiting the spectroscopic behaviour described. Holding such a colour filter before his eye, the observer views a brilliantly illuminated screen for a brief interval of time and then suddenly removes the filter while continuing to view the screen with his attention fixed at a particular point on it. He then observes on the screen a picture in colours which is the chromatic response of the retina to the light of the colour previously absorbed by the filter and which impinges on it when the filter is removed. Actually, as will become clearer presently, what the observer sees is a highly enlarged view of his own retina projected on the screen and displaying the response of the retina in its different areas produced by the incidence of the light of the selected wavelengths. By using a whole series of colour filters whose characteristic absorptions range from one end of the visible spectrum to the other, we are enabled to explore the behaviour of the retina over an extensive region under excitation by light of different wavelengths which in the aggregate cover the entire visible spectrum.

Why the phenomenon described above manifests itself is not difficult to understand. A colour filter completely absorbing a selected part of the spectrum when placed before the eye of the observer protects the retina from the incidence of light from that part of the spectrum, and if such protection continues for a sufficient period of time, it has the result of sensitising the retina for the reception of light of those wavelengths when the filter is removed. *Per contra*, light of wavelengths not absorbed by the filter being incident on the retina both when the filter is in position and after its removal, the visual sensation which it excites becomes enfeebled by the continued exposure. Accordingly, when the filter is removed, the visual response of the retina to light of the wavelengths for which its sensitivity has been enhanced is far stronger than the continuing response to the other wavelengths and manifests itself vividly to perception. The nature of the picture seen is determined by the part of the spectrum which is absorbed by the colour filter and differs enormously for the different filters employed in the study. The usefulness of the technique for the study of the functioning of the retina over its different areas is thereby greatly enhanced. Here, we should mention the essentially fugitive nature of the phenomenon. But this is no obstacle to the study of the effects. For, the image of the retina seen by the observer on removing the colour filter and which fades away is restored and can be examined again and again merely by putting back the filter in front of the eye for a little while and then removing it.

For an observer to study the results of using the colour filters in the manner explained above, a screen of the kind used for projection work containing a great many small glass spheres embedded in plastic is found to be particularly suitable. Placed facing the windows in a well-lighted room, such a screen is quite brilliant

and this indeed is necessary for any impressive phenomena to be observed. With a screen 175×120 cm in area, 350 cm is a convenient distance from the screen for the observer to station himself. The area of the screen under observation is then of sufficient width to include an enlarged picture of an extensive region of the retina. That what the observer notices when the filter is removed is a picture of his own retina becomes evident when it is remarked that the foveal disc is the central feature seen in every case. This is located at and around the point on the screen at which the observer's attention is fixed at the instant of withdrawing the filter from before his eye.

We shall in a later chapter return to the subject and discuss the significance of the results obtained by the technique using many different colour filters. Here we shall content ourselves with reproducing sketches in colour of the effects observed using colour filters with two of the numerous dyes employed in the study. The effects observed with a colour filter of crystal violet are exhibited in figure 3, and those observed with lissamine-green in figure 4. The foveal disc and the foveola at its centre are the most conspicuous features in both cases, the fovea appearing of a greenish-yellow hue in the phenomenon as seen with the crystal violet filter, and lemon-yellow as seen with the lissamine-green filter. The colours seen in the outer regions are also different in the two cases (plate III)*.

*For plate III, see p. 589.

CHAPTER IV

The basic visual sensations

From the standpoint of wave-optics, a beam of light has three specifiable characters. The first is the wavelength, the second is its intensity, in other words, the energy carried across unit area per unit of time, and finally, the state of polarisation of the light. Hence, if we accept the wave-optical description of light as determining the visual sensations excited by it, the two physiological characters of colour and brightness would be completely independent; the colour is associated with the wavelength, and the brightness with the intensity. But as has already been remarked in earlier chapters, wave-optics is no guide to the physiological perceptions of light. Considering the matter from the corpuscular point of view, we are concerned with two quantities: the first is the energy of the individual corpuscle, and the second is the number of corpuscles which contribute to the sensory impression produced. It then follows that we are no longer justified in regarding colour and brightness as completely independent sensations. Both have, of necessity, to be regarded as the cumulative effect of a great number of individual corpuscles. As the number which is effective increases, the sensation also may be expected to be intensified. In other words, as the total energy of the light-beam which is perceived increases, the sensations of colour and of brightness would both be progressively enhanced. *Vice versa*, as the energy of the light-beam progressively diminishes to zero, brightness and colour would both fade away.

The argument set forth above indicates the existence of a relationship between colour and luminosity as a direct and observable consequence of the corpuscular nature of light. This relationship may be demonstrated in an impressive and convincing fashion by the aid of a simple technique devised by the author. A portable screen of moderate size, 50×25 cm mounted on a stand is used for the observations. The material of the screen is a sheet of milk-white plastic with a smooth polished surface. It is illuminated by an extended source of light and is viewed by the observer who is close to the source, while the screen itself is at some distance and can be moved as far away as desired from him and the source. The screen is visible to the observer by reason of the light diffused by it. The image of the light source reflected at the surface of the screen is also seen at the same time. As the screen is moved away, its brightness as seen by the diffused light falls off rapidly, but the reflected image, though apparently diminished in size, continues to be seen with undiminished brightness. With these arrangements, the difference

in the perceived colours of the reflected and of the diffused light becomes obvious. It is readily noticeable even when the screen is close to the observer, and becomes more and more conspicuous as the screen is moved away from him, and the difference in brightness is therefore accentuated. When the screen is sufficiently far away from the source of light, its colour as seen by the diffused light is barely noticeable, while the reflected image exhibits the full colour of the original source.

The observations described above should be made in a completely darkened room of adequate size and the source of light should be covered up on all sides except that which faces the screen, so that no stray light can fall on the screen and vitiate the results. A sodium-vapour lamp may be used to study the phenomena with the monochromatic yellow light furnished by it. Likewise, a mercury vapour lamp may be used for observations with the green and with the violet radiations respectively; a plate of deep-blue glass placed before the lamp effectively isolates the λ 4358 violet rays, while a gelatine filter dyed with lissamine-green transmits only the green λ 5461 light.

A different technique which is very convenient in practice is the following. Diffuse light from the sky is admitted into a darkened room through a circular window covered with pin-headed glass at some height above the floor of the room. The light which emerges falls on a milk-white plastic screen placed facing the window and at a convenient distance from it. The observer faces the screen, placing himself at some distance from it; the illumination of the screen can be controlled over a wide range of values by the use of an iris-diaphragm covering the window which admits the light into the room. The opening of the iris can be varied from 20 cm down to 2 mm, thereby allowing the illumination of the screen to be reduced by any desired factor upto 10,000. When the iris is fully open, the plastic screen is brightly illuminated. Even so, it is much less bright than the aperture which admits the light into the room when viewed directly. The observer holds a colour filter before his eye and views the screen and the window alternately. Even when the iris-diaphragm is fully open, the screen is found to exhibit a colour much less saturated than that of the light which finds entry through the window. The observer then proceeds to close down the iris step by step, and views the screen and window alternately. The difference in their hues then becomes more and more conspicuous. Whereas the colour of the light entering at the window remains the same throughout, the colour of the screen becomes paler and paler until finally, it can only be recognised with difficulty, if at all.

The advantage of the second technique is that the colour-luminosity relationship can be followed over a greater range of brightness. It also allows the use of colour filters without any restriction. In other words, the phenomena under consideration are observed even when the light is not monochromatic in the strict sense of the term. It is worthy of remark that the effect is noticed in all cases, viz., whether the colour of the light which passes the filter is red, orange, yellow, green, blue or violet.

The colour-luminosity relationship which emerges from the studies described above enables us readily to understand various well known facts in the field of observational astronomy. The stars seen in the sky at night appear to the naked eye as mere specks of light, no colour being recognisable except in the case of the very brightest stars, e.g., Sirius which exhibits a distinctly bluish tinge, and Betelgeuse and Antares which exhibit reddish hues. Sirius which is the brightest of them all belongs to the spectral class AI, while its apparent visual and photographic magnitudes do not differ, being both—1.43. Betelgeuse and Antares belong to the spectral classes MII and MI respectively, and in both cases, the apparent visual and photographic magnitudes differ very considerably, those of Betelgeuse being 0.7 and 2.6, and those of Antares 0.98 and 2.78. If the surface-temperature of a star and the spectral class to which it belongs were the sole determining factors, we should expect a great many stars, especially those with very high or very low surface temperatures, to exhibit a recognisable colour. That they do not is a clear indication that for the visibility of colour, it is necessary that the star should be exceptionally bright.

The same considerations indicate that it should be much easier to recognise the colours of stars and especially the colour-differences between the stars if they are observed through telescopes of adequate power and hence appear much brighter. Indeed, it is well known that the colour difference between the components of a double star may be readily recognised if a telescope of adequate power is employed to observe them.

Finally, we come to the case of the so-called emission nebulae which emit light as the result of the optical excitation of the atoms of the gases of which they consist by the ultraviolet radiation from very hot stars in their neighbourhood. The gaseous nebulae which emit such light are in many cases spread over great volumes and have a low density. Even so, we should expect them to exhibit brilliant colours. Actually, however, when observed through telescopes of modest light-gathering power, they appear as patches of luminosity with scarcely any visible colour. We may here mention as examples, the Great Nebula in Orion, and the Ring Nebula in Lyra, both of which are objects visible in small telescopes. But when the light-gathering power of large telescopes is made use of, those objects do present striking colours which can be seen by the observer. Many years ago, the author had the privilege of observing these two nebulae with the great reflecting telescopes at Mount Wilson and was immensely impressed by the colourful appearance they presented (plate IV)*.

*For plate IV, see p. 590.

CHAPTER V

Fluctuations of luminosity in visual fields

The phenomena which forms the subject of the present chapter was observed and described by the author in a publication in which its origin was also discussed (*Curr. Sci.*, 33, 1964, page 65). As was there stated, the phenomenon is a striking demonstration of the part played by the corpuscular nature of light in its visual perception. It also plays a basic role in a subject of great importance, viz., the acuity of vision and its variations. The latter topic will be dealt with in a subsequent chapter, while the phenomenon itself will be considered here.

The experimental set-up needed for the study is quite simple. A white screen which has a uniform texture and a smooth surface is the principal requisite. It should be capable of diffusing the light which falls upon it uniformly over a wide range of angles. These requirements are admirably satisfied by a sheet of milk-white plastic which is a few mm thick and has a polished surface. A screen of this material 150×100 cm in area which is held vertically on a wooden stand and can be readily moved about is very suitable for the observations. The screen is illuminated by a source of light placed at some distance from it and is viewed by an observer who can take up any chosen position in the room, moving nearer to the screen or further away from it as desired. The source of light should be completely covered up except on the side facing the screen, an aperture being provided on that side for the emergence of light. These arrangements ensure that no stray light falls on the screen. It is desirable also to provide for the illumination of the screen being varied over a wide range of values. This is most conveniently secured by the use of an iris-diaphragm to cover the aperture through which the light emerges. A sheet of ground-glass interposed between the light-source and the iris-diaphragm is a useful adjunct as it helps to diffuse the light uniformly over the aperture of the iris. A maximum opening of 10 cm and a minimum of 2 mm for the iris enables the illumination to be varied by a large factor as may be needed.

The observations should be made in a completely darkened room, and it is desirable that they are commenced only after some time has been allowed for the disappearance of the after-effects of any previous exposure of the eyes of the observer to bright light. A sodium-vapour lamp or a mercury-vapour lamp with appropriate colour filters may be used for observations with monochromatic light, while an ordinary tungsten filament lamp suffices for observations with white light. Colour filters may be inserted in front of the iris, if it is desired to isolate a particular part of the spectrum of white light.

A screen which is uniformly illuminated and which diffuses the light falling on it through a wide range of angles should appear to a distant observer as a continuous area of light which does not exhibit any variations. It is a surprising fact that this anticipation is not realised and that the screen actually exhibits over its entire area a display of varying luminosity which alters from instant to instant in a chaotic fashion. The nature of the patterns of variation of brightness over the area and the manner they change with time is found to depend greatly on the strength of illumination of the screen, as also on the distance from which it is viewed by the observer. The spectral character of the illumination has also a noticeable influence on these features.

That the phenomenon is a consequence of the corpuscular nature of light is *prima facie* inferable from its observed features. This inference is confirmed when we proceed to consider in detail the consequences which would follow from the recognition that our visual sensations represent the conjoint effect of a great many individual light-corpuscles which reach the observer's eye and are there actually perceived. The number of individual light-corpuscles sent out by a source and reaching the screen under observation in any given time-interval would, of course, be very large. The number is proportional to the light-flux incident on the screen. But if we consider only a small element of the area of the screen, the number is reduced in proportion to the area of the element. Then, again, only a very small fraction of this number can reach the eye of the observer. For, the screen diffuses the light over a wide range of angles and if the distance of the observer from the screen is large, the number actually finding entry into the pupil of his eye would be but a minute fraction of the whole. We have also to recollect that of the light-corpuscles reaching the retina, only a small fraction would actually be absorbed and be effective in perception. When all these considerations are taken into account, and it is also remembered that the eye can, in appropriate circumstances, take note of rapid variations in the perceived luminosities, the possibility of fluctuations of luminosity being perceived at various points on the area of the illuminated screen becomes evident.

A significant fact of observation is that the patterns of fluctuating luminosity seen on the screen are on a larger scale, in other words appear to consist of larger individual areas, when the illumination of the screen is at a low level. *Per contra*, if the screen is more brightly illuminated, the patterns of varying intensity are on a much finer scale. A second fact of observation is that the patterns of varying luminosity are on a much larger scale when the observer is far removed from the screen than when he is close to it. Finally also, it may be remarked that if the illumination of the screen is at a high level and the observer is also close to the screen, the patterns of varying brightness are on an extremely fine scale and need attentive observation to enable them to be discerned. All these facts agree with what we should expect on the basis of the considerations set forth above.

The observed dependence of the fluctuations of luminosity on the spectral character of the light falling on the screen is a further confirmation of the origins

of the phenomenon. The simplest way of exhibiting this dependence is for the observer to view a white plastic screen placed in a darkened room and facing a window through which skylight is admitted, its illumination being controlled by opening or closing an iris-diaphragm which covers the window. The illumination is first adjusted to be at such a level that the fluctuations are visible on the screen but on a fine scale and are not very conspicuous. On placing a filter of blue glass before the observer's eye, it is found that they become far more conspicuous and are also on a larger scale. This is the result to be expected. For, the blue-violet end of the spectrum is the least luminous part of it, thereby indicating that a much smaller proportion of the energy appearing in that part of the spectrum is actually perceived as light. Further, the energy of an individual corpuscle is also greater in that region. Hence, the number of corpuscles actually effective in vision is relatively much smaller than for other parts of the spectrum. The more pronounced character of the fluctuations of luminosity which are observed thus becomes intelligible.

Introduction of a red filter before the observer's eye has a less striking influence on the fluctuations of luminosity visible on the screen than in the case of a blue filter. Why this is the case hardly needs to be elaborated in view of the remarks already made. But it should be mentioned that the fluctuations visible through a red filter are more conspicuous than when viewed without the filter, if the level of illumination of the screen is so low that the sensory impression produced by red light itself becomes extremely weak. The effects then seen are comparable with those observed through a blue filter.

CHAPTER VI

Colour and luminosity in the spectrum

The ability to perceive and recognise colour is a characteristic feature of human vision. It follows that the elucidation of the origins of colour is a highly important part of the science of vision. Already, in the earlier chapters, we have encountered certain aspects of the subject and we now proceed to concern ourselves with it in greater detail.

When white light emitted by a solid body at a high temperature is examined through a spectroscope, we observe a band exhibiting varied colours which is referred to as its spectrum. An essential feature of this spectrum is that the colours observed in it form a continuous sequence. The number of colours which can be distinguished from each other is fairly large. If, for example, the spectrum is divided up into fifty strips in the manner already described and illustrated in an earlier chapter, each of these strips exhibits a colour visibly different from those of the adjoining strips. Such a sub-division of the spectrum also represents a partition of it into sections in which the energy of the light-corpuscles which give rise to the observed colour alters by equal increments. It is thus evident that the perception of colour depends upon and is linked in the closest fashion with the corpuscular light-energy.

It follows from the foregoing remarks that the subject of colour falls naturally into two distinct divisions. The first division concerns itself with the pure spectral colours, in other words with the sensations excited by light in which the corpuscles all possess the same energy. The second division concerns itself with the colours of composite light, in other words with the hues exhibited by light in which the corpuscular light-energies are not all the same but differ widely. It is obvious that this second part of the subject needs to be dealt with separately. It is a more complex field of enquiry than the first and it would be both illogical and fruitless to attempt to deal with it until the subject of the pure spectral colours has been fully explored and elucidated. Accordingly, in the present chapter and in the succeeding one, we shall limit ourselves to the pure spectral colours which, as we shall see, themselves present a wide field of investigation. What the colours of composite light are and how they are generated will be dealt with in later chapters.

Highly remarkable and significant changes are observed in the spectrum of white light when the level of brightness at which it is viewed is progressively lowered. We shall first describe these changes and later proceed to make some comments regarding their significance.

The technique of observation adopted is quite simple. A source of light which is useful in such work is a tungsten filament lamp of the kind employed in projection lanterns. The lamp contains a group of coiled-coil filaments placed side by side which together make an extremely powerful source of white light of small area. The lamp is kept cool by a fan and may be brought quite close to the slit of a wavelength spectrometer of the well known type. The resulting spectrum may be viewed directly on the ground-glass screen usually provided with the instrument for focussing the spectrum. As the dispersion of the instrument is adequate, it is possible to open its slit to a width of 1 mm without appreciably affecting the purity of the spectrum. In these circumstances, it appears extremely brilliant on the screen. The brightness may be reduced by adopting one or another of three devices, either together or separately. The first is to move the lamp away from the slit of the spectrometer to a considerable distance up to say two metres. The second is to narrow the slit of the spectrograph down to a tenth of a mm. The third device is to insert a piece of ground-glass in an appropriate position between the slit and the lamp when these are sufficiently far apart. When all these devices are simultaneously made use of, the spectrum seen on the ground-glass is of greatly reduced brightness. Nevertheless, if the room has been darkened, and the observer uses a hood of black cloth to keep out stray light, there is no difficulty whatever in his viewing the spectrum and taking note of its features. We shall describe the spectrum as seen at five different levels of brightness, beginning at the highest and ending with the lowest.

At its most brilliant level, the spectrum exhibits its maximum extension at both ends. The features noticed at this stage which are of particular interest and importance are the following: By far the brightest part of the spectrum is the region which is yellow in colour. This region covers an appreciable width of the spectrum. An orange-yellow strip on one side and a greenish-yellow strip on the other side are also conspicuous. Beyond these areas, the red and green sectors appear. The rest of the spectrum consists of regions which exhibit three distinct colours: the first region is a bright blue, the second is a dark blue which may be termed as indigo, while the third region is of a violet colour. The three regions are of progressively diminishing intensity, but between the blue and indigo regions, a fall of intensity is very clearly noticeable, while a second fall of intensity is also noticeable between the indigo and violet regions.

At the second stage in the order of diminishing intensity of the spectrum, it exhibits a visible contraction at its red end. The yellow of the spectrum is still the brightest part of it, but it is not now so conspicuous. The orange-yellow and greenish-yellow parts are still observable, but they have definitely contracted. A particularly noteworthy feature is that the blue part of the spectrum has visibly contracted, its place being taken by the indigo and violet parts moving inwards. The falls of intensity between the blue and the indigo, and between the indigo and the violet are however still noticeable.

At the third stage of diminishing intensity, a further contraction of the

spectrum at its red end is noticed. The yellow of the spectrum is still seen, but it does not appear as more brilliant than the red and the green on its two sides. These two colours appear redder and greener respectively than in the spectra at the earlier stages. The bright blue of the spectrum has disappeared completely and the regions beyond the green which are now of diminished intensity exhibit only the dark blue and violet colours.

At the fourth stage of diminishing intensity, the red of the spectrum has contracted further, and the yellow is barely discernible. Both the red and the green appear of a richer colour than previously and are of comparable intensities. The spectrum beyond the green is very weak and appears of a violet colour throughout. The falls of intensity noticed in the earlier stages in these regions are no longer visible.

In the fifth stage of the series which is the lowest in respect of intensity, the red of the spectrum continues to be visible, but it is much shortened and of greatly reduced intensity. The yellow of the spectrum has disappeared. But the green continues to be visible and is now the brightest part of the spectrum. The part of the spectrum which follows it is of low intensity and its colour is barely noticeable. This region is also of visibly diminished extension.

Another technique which has also been successfully employed in these studies makes use of a tubular lamp 25 cm in length carrying a luminous tungsten filament stretched along its axis. The observer holds a replica-grating before his eye and views the diffraction-spectra of various orders seen on either side of the glowing filament. The brightness of the spectra can be altered over a great range by varying the electric current which heats the luminous filament. The brightness of the spectra as actually perceived can also be diminished considerably by the observer with the grating held before his eye moving away to a great distance from the filament. *Vice versa*, by coming close to it, the brightness can be greatly enhanced. The visual comparison of the colours seen in the spectra of different orders is also found to be extremely useful. For, they differ greatly in their brightness.

A particularly interesting case is that in which the filament is at a low temperature and emits a weak glow of red colour. The spectra of the first order then exhibit only the green region, the rest of the spectrum having gone completely out of sight. The progressive weakening and ultimate disappearance from sight of the red part of the spectrum as the level of illumination is lowered can be followed by diminishing the heating current through the filament step by step until the green of the spectrum is its only surviving part. The second-order spectra being much weaker than those of the first order exhibit these changes at an earlier stage.

The very striking changes in the intensity of the yellow sector of the spectrum as we pass from the highest levels of brightness down to lower levels are impressively exhibited by the same technique. Beginning with the filament at the highest temperature which it can withstand, the observer also being close to the lamp, the

yellow is observed to be the dominant feature in the spectrum. Besides being extremely bright, it is observed to modify the colour of the regions of the spectrum on either side to a notable extent. As the filament current is diminished, or if the observer moves away from the lamp, the dominance of the yellow becomes much less evident. Later, a stage is reached at which the yellow is barely visible as a thin strip separating the red and green regions of the spectrum, these now exhibiting hues which appear highly saturated. Finally the yellow disappears completely. At still lower levels of brightness, the red also becomes weaker and finally disappears, as already stated.

Observations by the same technique confirm the remarkable finding that the colours observed in the short-wave range of the spectrum may be either blue or indigo or violet according to the circumstances of the case, the violet replacing both indigo and blue when the intensity is low, and finally itself becoming almost colourless. These effects can be followed by varying the heating current through the filament. They are also manifest when the colours of the first and the second-order spectra are compared with each other. The observations also confirm the appearance of two distinct falls of intensity which appear respectively between the blue and the indigo and between the indigo and violet when the spectrum is sufficiently bright for these colours to be distinguishable.

Finally, it may be remarked that the general weakening of all colour sensations which goes hand in hand with diminishing brightness is strikingly manifest when we compare the spectra of the different orders with each other.

It appears appropriate to conclude the present chapter with some comments on the trichromatic theory of colour-perception. As has already been remarked, the colours perceived in the spectrum stand in the closest relationship with the corpuscular energy. Hence, every colour which can be perceived in the spectrum of white light must necessarily be regarded as distinct from every other, and the total number of independent colour sensations is therefore limited only by our ability to perceive them as distinct. Hence, to postulate that there are only three independent colour sensations from which all other colour sensations can be derived by superposition is clearly an arbitrary and unjustifiable hypothesis.

The falsity of the trichromatic theory becomes manifest when we consider the region of the spectrum which appears to us as yellow in colour. According to the trichromatic hypothesis, yellow is not an independent sensation and is derived by a superposition of the red and green sensations. We have only to compare this assumption with the actual facts of the case as they emerge from the observations described in the present chapter. We have seen that in brilliant light, the yellow is the most luminous part of the spectrum far brighter than either the red or the green in it. Indeed, it is possible to go further and view the spectrum of white light at extremely high levels of intensity, as, for example, by observing a tungsten filament glowing at a white heat through a replica diffraction grating held before the eye. The spectrum is then seen as a brilliant band of yellow colour over its whole length with relatively feeble terminations of red and blue at its ends.

Per contra, as we have seen, at low levels of illumination, the yellow is barely observable in the spectrum, while the green and the red are still to be seen exhibiting their characteristic hues. These facts of observation demonstrate the fallacy of describing the yellow of the spectrum as a secondary or derivative sensation.

CHAPTER VII

The colours of interference

The role of outstanding importance in vision played by the yellow sector of the spectrum is strikingly illustrated by a study of the interference patterns of the kind described earlier and illustrated in Chapter II when observed in white light. The colours exhibited by such patterns are a familiar phenomenon, but surprisingly enough, though they have been known for three centuries, attention does not appear to have been drawn to the special features which characterise these patterns and the recognition of which is necessary for their real nature to be understood.

In a well known form of the experiment, the air-film is that enclosed between two surfaces, of which one is plane and the other spherical with a large radius of curvature. In these circumstances, the interferences take the form of rings which are concentric around the region of actual contact of the two surfaces where the film has zero thickness. This central region appears black in the pattern. Sir Isaac Newton devoted the second book of his classical treatise on optics to a description of these rings and hence they are usually known by his name. But neither Newton nor any of the numerous other observers who have described and discussed the effects observed in the experiment make any reference to the major feature of the phenomenon, viz., the manifestation of a series of maxima and minima of luminosity in the field covered by the pattern. These alternations of luminosity determine the characters of the interference pattern and the alternations of colour observed are related to the alternations of luminosity in a manner which clearly indicates that the latter constitute the basic phenomenon and that the colour differences are only incidental consequences.

The diameter of the interference rings and the area over which they can be perceived in white light depend on the difference in curvature of the surfaces enclosing the air-film. The pattern and the rings may be so small that they can only be seen through a magnifier. On the other hand, the pattern and the rings may be on such a large scale that they can be seen and examined without any optical aid. The author has found that by merely holding together two pieces of thick plate glass in contact at the correct relative orientation, it is possible to obtain circular ring patterns on a very large scale. This is a consequence of the surface of the plates being cylinders of large radius which when held in crossed positions enclose between them an air-film of thickness depending only on the radial distance from the point of contact. This arrangement is found to be

particularly useful for the studies presently to be described.

A surprising fact is that when the interference rings are on a small scale and are viewed by an observer from the usual distance of distinct vision, they are seen by him as a succession of bright and dark rings, five or six in number, but not exhibiting any visible colour. But when the same pattern is held close to the eye and viewed through a magnifier, the colours spring into view. What these observations signify is that the interferences as seen with white light are essentially a pattern of varying intensity of illumination analogous to those observed with monochromatic light but with the difference that the successive rings, instead of all being equally conspicuous, progressively diminish in visibility, thereby limiting the number that can be seen and counted.

Inspection of the interference patterns exhibited by air-films of varying thickness reveals in all cases that, following the region of actual contact where the film does not reflect light, we have four or five alternations of the brightness or intensity of the reflected light. Very conspicuous is the first minimum of intensity which is nearly but not quite black. Following this again, there are three other minima of intensity which are progressively less conspicuous but of which the positions can be determined with precision. A fifth minimum of brightness can be recognised but with some difficulty.

The manifestations of colour in the patterns observed with white light are very clearly related to the variations of luminosity in the field. What we may describe as a cycle of colours begins at each minimum of luminosity and ends at the next minimum, where a fresh cycle commences and proceeds to the next and so on. At least six such cycles are clearly recognisable, beyond which a few more can be glimpsed. The characters of the cycle of colours show a change as we proceed from the first to the second and then to the third, while the subsequent cycles resemble each other pretty closely. In the first three cycles, the yellow colour at the place of maximum luminosity is evident. At each minimum, we begin with a blue or bluish-green and pass on to the yellow, and then through orange to red at the next minimum where the cycle terminates. In the later cycles the yellow is not visibly manifested and we observe only an abrupt change of the colour from green to red.

The relationship between the interference pattern as seen by white light and as observed in monochromatic yellow light is made strikingly evident when arrangements are made by which the interferences as observed with white light and with monochromatic light are brought into juxtaposition so that a direct visual comparison between the two is made possible. It is desirable that the interferences should be on a fairly large scale so that they can be seen without any optical aid. Interferences of the type illustrated in figure 1(A) and (B) of Chapter II are suitable and convenient for the purpose in view. One half of the pattern under study is illuminated by the diffuse white light from a tungsten filament lamp and the other half by the yellow light from a sodium vapour lamp, the two halves meeting sharply along the dividing line between them. At least four successive

orders of interference in the white light patterns show recognisable minima of illumination, and with the arrangements described, it is found that they are completely coincident with the four corresponding dark lines in the patterns as seen with the sodium light, no break or shift appearing as we move from one part of the pattern to the other. In other words, white light behaves as if we could assign to it a specific wavelength located in the yellow sector of the spectrum.

These findings are confirmed by precise measurements of the positions of the minima of illumination in the white light patterns and comparing them with the minima as observed with monochromatic light of various wavelengths. For this purpose, the selected radiations are, besides the yellow of sodium vapour, the yellow and green radiations of a mercury vapour lamp, these being separated from each other by the use of a monochromator. The pattern which has been measured is the Newtonian ring-system which surrounds the point of contact between two lenses having curved surfaces. This pattern is on a sufficiently small scale to be suitable for exact measurements being made on it with a Hilger micrometer. The results are shown below in table 1.

Table 1. Diameter in mm

Dark ring	White light	λ 5893	λ 5780	λ 5461
No. 1	3.357	3.346	3.315	3.229
No. 2	4.651	4.639	4.604	4.489
No. 3	5.590	5.574	5.538	5.389
No. 4	6.490	6.398	6.358	6.176

It will be seen from the data exhibited in table 1 that the positions of the minima of illumination as observed with the sodium light and with white light agree fairly well. The agreement is not so good with the yellow light of a mercury lamp, while they diverge widely from the positions of the minima as observed with the green λ 5461 radiation.

CHAPTER VIII

The discrimination of colour

We shall concern ourselves in the present chapter with the following questions. How sensitive are our eyes to differences in colour? What are the factors which determine or limit this sensitivity? It is obvious that these questions can only be answered by systematic observational studies, though it is possible to venture on some general considerations based on pure theory.

So long as we restrict ourselves to the pure spectral colours, we can base ourselves on the fact of observation that the progression of colour in the spectrum corresponds to a progression in the energy of the corpuscles of light which are perceived, in other words that there is a one-to-one correspondence between the perceived colour and the energy of the corpuscles which are absorbed by the retina and excite the sensation of light. This being the case, any lack of precision that is noticeable in the perception or discrimination of colour may reasonably be attributed to a corresponding lack of precision in the energy-transformation which results in the observed visual sensation. The absorption of light by the molecules of a pigment present in the retina may be assumed to precede such transformation of energy. A factor which is inevitably present is the energy of the thermal agitation of the molecules of the absorbing material. Hence, we must be prepared to find that the energy of the incident corpuscle of light is either added to or diminished by the energy of such thermal agitation in the act of absorption. The situation may be expressed by the formula:

$$h\nu^* = h\nu \pm kT.$$

Here ν is the frequency of the incident light, ν^* is the frequency of the light as actually perceived, k is the Boltzmann constant and T is the absolute temperature of the retina. Dividing out both sides of the equation by Planck's constant h , we obtain

$$\nu^* - \nu = \pm kT/h.$$

Expressing the quantities on both sides of the equation in terms of wave-numbers, we find from the equation that our perception of colour in the spectrum is liable to an uncertainty due to the thermal agitation existing in the retina of the order of ± 215 wave-numbers. If expressed in wavelengths, the magnitude of this uncertainty would increase progressively as we proceed from the violet towards the red end of the spectrum. At both of these ends, the luminosity of the spectrum

is very low, and this is especially the case near the violet end. Taking 4200 and 6500 Å respectively as the limits within which a critical study of colour discrimination is possible, the uncertainty of ± 215 wave-numbers would be equivalent to ± 38 Å at the violet end of this region and of ± 89 Å at the red end, with intermediate values elsewhere.

We may also state the same result in a different way. By dividing the entire spectrum into a series of strips of which the separation is 215 wave-numbers, we obtain 50 strips in all. The argument set forth indicates that an observer viewing the spectrum thus divided would find each strip differing visibly in colour from the strips on either side of it. An observational test of this statement is readily possible by making use of the optical device described and illustrated in Chapter II which enables the spectrum to be transformed into a succession of bands following each other at a constant wave-number separation. This separation can be altered at will. We can therefore proceed step by step and compare the colour of each band with those of the bands on either side of it. So long as the number of bands in the spectrum is not too great, a perceptible difference of colour is then actually observed. This is definitely the case when the number of bands which can be counted in the spectrum is as large as 50, which corresponds to the wave-number separation of 215.

The argument set forth above assumes that the absorption of light at all points of the spectrum would be influenced by the thermal agitation of the molecules to the same extent everywhere. That this would actually be the case is however most unlikely. For, the absorption of light in the visible spectrum would primarily be the result of a change in the electronic energy levels of the absorbing molecules. Such change need not necessarily be accompanied by a change in the energy of their internal vibration or of their translatory movements. The energy taken up from the incident light would then be fully available for its perception, and a high degree of accuracy in the recognition of colour differences could be expected. On the other hand, if the absorption of light involves also changes in the energy of internal vibration and of translatory movement, the same measure of precision cannot be expected. We are thus led to infer that the estimate of ± 215 wave-numbers should be regarded as an upper limit and not as a definitive value for all parts of the spectrum. We may expect a much better performance in respect of the accuracy of colour perception in the regions of the spectrum which correspond to the changes of the electronic energy levels alone and a lesser degree of accuracy in the regions of the spectrum remote therefrom. Especially at and near the extremities of the spectrum where the luminosity is low, in other words where the absorbing power is weak, we may reasonably expect a close approach to the upper limit of ± 215 wave-numbers in the uncertainty of colour perception.

The considerations set forth above indicate that a quantitative study of the power of colour discrimination over the entire range of the visible spectrum would throw much-needed light on the absorptive properties of the visual pigments present in the retina and may even assist in their identification. The

optical technique of study making use of a banded spectrum, though useful for a qualitative survey of colour perception, cannot serve for a precise quantitative study. Accordingly, two other methods have been devised and adopted and will presently be described.

The first of the two techniques adopted is perhaps the simplest that could be thought of. It depends on the presentation to the eye of the observer of a limited part of the spectrum and then very quickly afterwards an adjoining region of the spectrum. He has then to decide whether or not he perceives a change of colour. The observations are made with a spectrometer having a calibrated wavelength drum. A slit of adjustable width is placed in the focal plane of the observing telescope. This admits a narrow strip of the spectrum which is viewed by the observer through the eye-piece of the instrument. A rotation of the wavelength drum in one direction or the other enables the smallest change of wavelength which produces a detectable change of colour to be read off. By taking the average of several readings, fairly reliable values can be obtained. The width of the slit most suitable for the observations is something in the nature of a compromise. If it is too narrow, not enough light comes through, and if it is too broad, it admits light over a range of wavelengths comparable with the quantities sought to be measured. Despite this source of uncertainty, the technique is found to be capable of yielding useful results.

The results of a set of measurements made in the manner explained are exhibited in figure 5. The ordinates in the graph show the wavelength shifts required to produce an observable change of colour, while the abscissae indicate the part of the spectrum under observation. The readings were taken at intervals of 100 Å. The noteworthy features in the graph are the very conspicuous dips in the wavelength region between 4900 and 5000 Å and in the yellow of the spectrum around 5800 Å. Higher elevations appear elsewhere and especially in the parts of

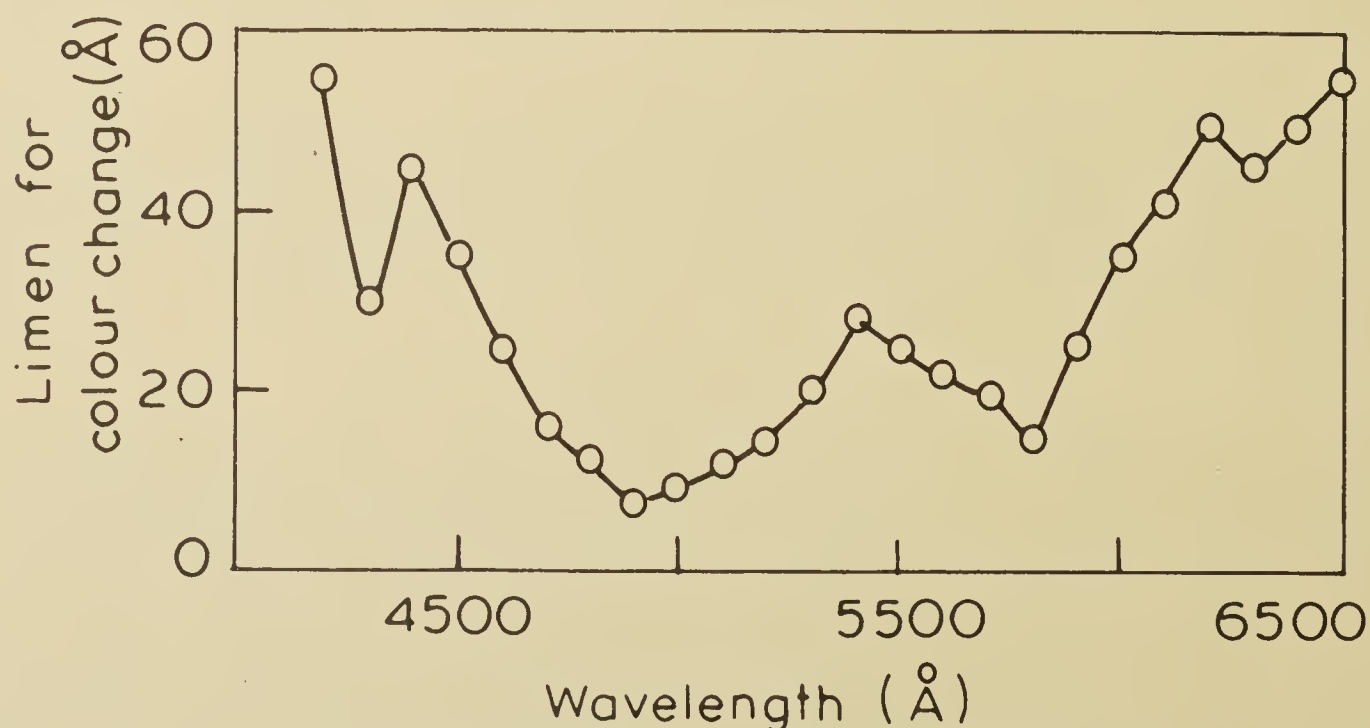


Figure 5. Discrimination of colour in the spectrum.

the spectrum near its two terminations. The lesser dips in the curve at 4300 Å in the short-wave region and at 6300 Å in the long-wave region correspond to points in the spectrum at which fairly rapid changes in colour are visually noticeable.

The ideal arrangement for determining the sensitivity of the eye to the colour differences which present themselves in the spectrum is to compare light of each wavelength with light of an adjacent wavelength by presenting both side by side with a sharp dividing line of separation, as in ordinary photometric practice. It is necessary that the intensities of the lights under comparison should first be equalised to ensure that differences in luminosity are not mistaken for differences in colour. Two monochromators have been used for a study of this kind, one being a quartz monochromator of large aperture by the firm of Hilger and the other a double-monochromator with glass prisms supplied by Kipp and Zonen. The instruments were so placed that the monochromatic pencils emerged from them in perpendicular directions. This enabled the comparisons between them to be made using a Lummer–Brodhun cube as the photometric device. The field was effected by varying the widths of the entrance-slits of the two circular ring. The original light-sources used with both instruments were of the same kind, viz., tungsten-filament lamps emitting white light of great intensity. The equalisation of the intensities of the light appearing in the two parts of the field was effected by varying the widths of the entrances-slits of the two instruments. It was checked at each stage by direct observation of the field of view when the wavelengths were the same. The light issuing from the Hilger monochromator could be shifted by steps of 100 Å at a time and was made the standard of reference. The wavelength of the light issuing from the Kipp and Zonen instrument could be varied by rotating the drum provided for the purpose. The smallest wavelength shift producing an observable difference in colour was determined, six successive settings being made at greater wavelengths and six at smaller wavelengths. A systematic series of observations was thus made, covering the spectrum from end to end. This was repeated a second time to check the reliability of the determinations.

The results obtained in the manner set forth above are shown as a graph in figure 6. A comparison with those shown earlier in figure 5 shows a gratifying measure of agreement. In both figures, the wavelengths at which the eye perceives the most rapid changes of colour are the same, viz., at 4900 Å and 5800 Å. At 5400 Å, both curves exhibit a turning point where the colour changes but slowly. Dips of a minor character appear at 4300 Å and 6300 Å in both figures. In both figures also, the curve rises steeply on the two sides of the dip at 5800 Å and somewhat less steeply on the two sides of the dip at 4900 Å. The asymmetrical shape of the graph on either side of the wavelength of 4900 Å is also clearly exhibited in both figures.

The two graphs differ from each other in respect of some minor details. But this is not surprising, since the techniques of observation employed were not the same. Further, the levels of illumination at which the determinations were made

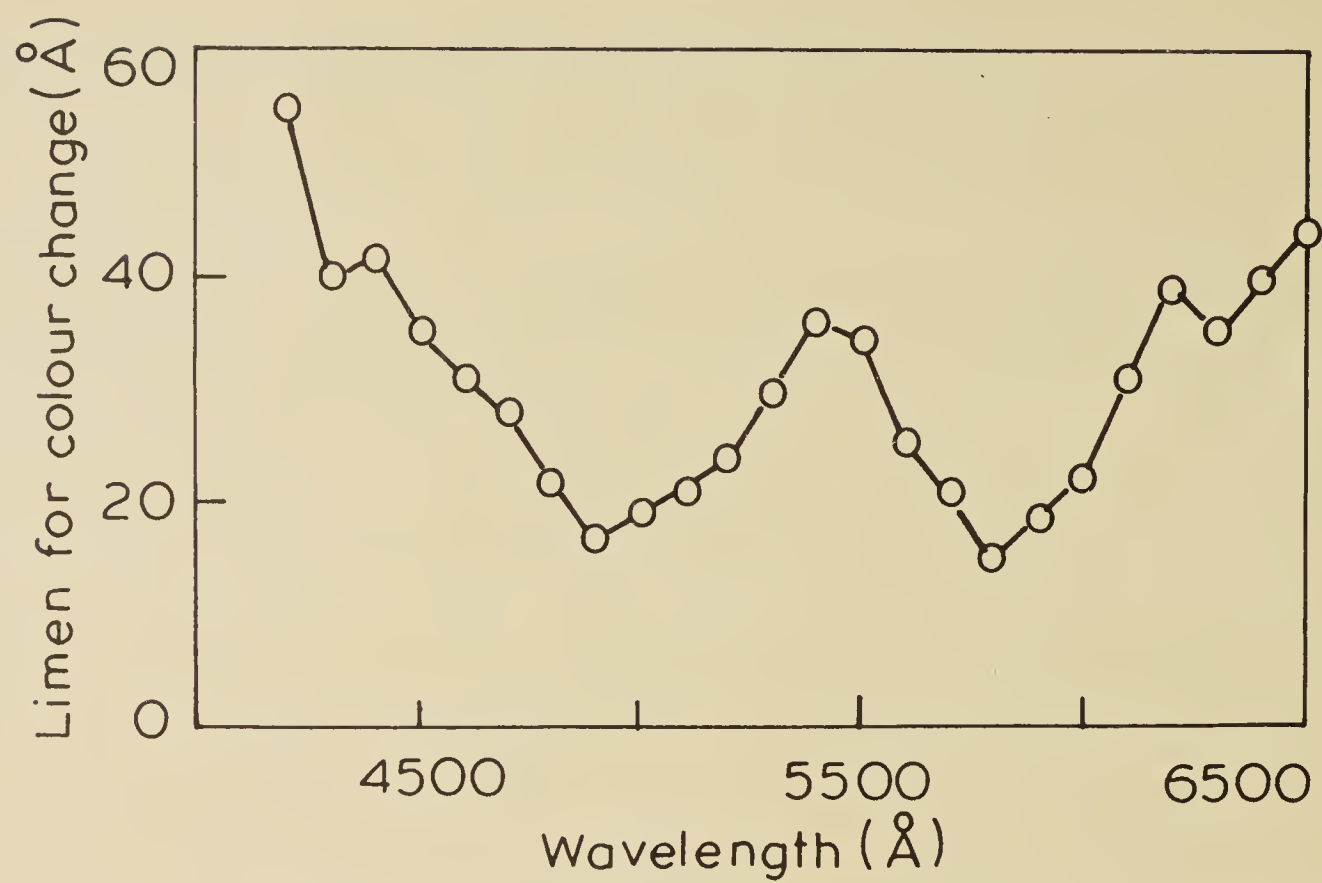


Figure 6. Discrimination of colour in the spectrum.

not identical. With the more elaborate technique using two monochromators, the illumination of the field under observation is at a distinctly lower level than when a strip of the spectrum is viewed directly through a slit. As was already been noticed in an earlier chapter, the absolute luminosity of the spectrum has a notable influence on the colour sequence observed in it.

From the data exhibited graphically in figure 6, table 2 has been prepared to exhibit the points in the spectrum at which the graph exhibits noteworthy features, viz., a maximum or a minimum. The wavelength has been shown as also the corresponding wave-number. Figure 6 shows the data in terms of wavelengths and wavelength differences. But in table 2, the wave-number, wave-number differences and their percentages have been shown as they are more significant.

It will be seen that all the figures in the fourth column except the last are much

Table 2. Colour sensitivity of the eye.

Colour	Wave-length (Å)	Wave-number	Detectable wave-number difference	Percentage difference
Red	6300	15873	± 88	0·6
Yellow	5800	17242	± 39	0·2
Green	5400	18519	± 174	0·7
Blue	4900	20408	± 71	0·35
Violet	4300	23256	± 216	0·9

less than the wave-number difference of 215 to be expected if the thermal agitation of the retina exercises its maximum effect on colour perception.

We now proceed to sum up the results which have emerged in this chapter. The progression of colour in the spectrum of white light is the sensory perception of the progressive increase in the energy of the corpuscles of light as we pass from the red to the violet. It may be inferred that the precision exhibited by the colour sense is also a measure of the precision with which the energy of the light-corpuscles becomes available for the perception of light without diminution or addition. The only limiting factor which may lead to uncertainty and needs to be considered in this context is the thermal energy of the molecules which absorb the light and enable it to be perceived. Calculations show that the uncertainty due to this factor is more than sufficient to account for the observed lack of precision of the colour sense at all points in the spectrum. It may be inferred from this that the graph exhibiting the varying power of colour discrimination over the spectrum exhibits the extent to which the absorptive processes resulting in the perception of light are actually affected by the thermal agitation in the retina. The variations in the power of colour discrimination over the range of the visible spectrum are thus indicative of the spectral behaviour of the visual pigments in the retina and can assist us in their identification.

We may appropriately conclude this chapter with some comments on the photochemical theories of colour perception which have in the past found a place in the literature of the subject. These theories contemplate that the incidence of light on the retina results in a photochemical break-up of the material contained in it and that such break-up is the primary process which enables light to be perceived. One need not question the possibility of such photochemical reactions taking place in the retina and of the subsequent regeneration of the materials thus decomposed. But what should be called into question is the assumption that such chemical changes play the primary role in the visual perception of light and that the material undergoing such modifications is itself the "visual pigment" which plays an active role in such perception. That these assumptions are unnecessary and indeed untenable is indicated by various considerations. It will suffice here to point out that if what has been set forth in the preceding paragraph regarding the perception and discrimination of colour is valid and acceptable, *ipso facto*, all photochemical theories of vision must stand rejected. For, any chemical reaction excited by light would necessarily take up a proportion of the energy of the incident light-corpuscles and this proportion would depend on the nature of the reaction and on the part of the spectrum in which the incident light appears. In such circumstances, the continuous progression of colour in the spectrum and the high degree of precision exhibited by the colour sense would remain unexplained.

CHAPTER IX

The perception of polarised light

One of the most remarkable of our visual faculties is the ability to recognise polarised light and to locate its plane of polarisation. It is the foveal region of the retina that exhibits this power which, it may be remarked, is limited to light appearing in the blue sector of the spectrum. The fovea is the most useful part of the retina and the spectral region manifesting this property is also distinguished by its being the most colourful and yet the least luminous part of the entire spectrum. Clearly, therefore, the process by which the fovea is enabled to recognise the presence of polarisation in light appearing in a restricted range of wavelengths and is unable to achieve the same results in other parts of the spectrum is of great significance. The investigation of which the results will be set forth in the present chapter has revealed that the perception of polarisation is effected by a physiological process which stands in the closest relationship to the perception of colour and luminosity in the same spectral region.

Haidinger's brushes: The blue colour of the sunlit sky has its origin in the scattering of sunlight by the molecules of the earth's atmosphere. Skylight accordingly exhibits a high degree of polarisation when observed in a direction transverse to the rays of the sun. As a consequence, observation of the parts of the sky which exhibit the maximum degree of polarisation should enable us to demonstrate the ability of our eyes to perceive and determine the state of such polarisation. The effects thus arising are best looked for in the forenoon of any bright clear morning when the sun is well up above the horizon. The observer should stand with his back to the sun and view the regions of the sky where the maximum of polarisation is to be expected. These regions would evidently lie along the arc of a great circle which runs at a slant across the sky. Scanning this circle rapidly with his eyes, the observer will notice a band along the circle which appears bluer than the rest of the sky and which is bordered on both sides by bands of the same width exhibiting a distinctly yellowish hue. On fixing his attention at a particular part of the circle to his left, it will be found that the colours seen in that region soon fade away from sight. The observer should then turn quickly and fix his attention on the part of the great circle to his right which is 90° away from the original point of fixation on the left. He will then notice in this region a very striking phenomenon, viz., a dumbbell-shaped blue brush of light having its axis on the great circle of maximum polarisation of skylight and

crossing this brush a yellow brush of light of similar shape with its axis transverse to that circle. These brushes are conspicuous when first seen, but when the observer continues to gaze at them, they fade away from sight. He should then again turn quickly to the region on the circle previously viewed. He will then notice in that region a similar conspicuous manifestation of the blue and yellow brushes crossing each other. This alternation between the left and the right can be repeated as often as desired.

Studied in the manner described, the nature and origin of the phenomena become clear. What the observer perceives is an enormously enlarged picture of the foveal region in the retinae of his own eyes projected on the sky and manifesting itself by reason of the visual response of the fovea to the light incident on it. The spectral character of that light, its state of polarisation and the orientation of the plane of polarisation in relation to the fovea are the factors which determine the nature of the picture perceived. The circumstances in which it is observed indicate that the conditioning of the eye by an earlier exposure to polarised light also plays a highly important role. The entire light of the spectrum is polarised, but the part of the spectrum not included in the range of wavelengths between 400 and 500 $m\mu$ behaves quite differently from the part which is included in that range. It is the latter part of the spectrum that evokes a powerful visual sensation in the two sectors of the fovea of which the axis is parallel to the direction of vibration in the incident light. The two other sectors of which the axis is perpendicular to that direction are not thus excited. Since these differences appear only in the blue-violet sector of the spectrum, the visual sensation in the former case manifests itself as a brush of a bright blue colour. In the latter case, the absence of any sensation in the blue region of the spectrum results in only the rest of the spectrum being perceived. The manifestation of a yellow brush crossing the blue brush is thus accounted for.

The blue and yellow brushes and the regions in the fovea which they represent interchange positions when the observer shifts his vision from the part of the sky on his left to another on his right located 90° away from it. The regions of the fovea which are not excited in one case are those excited in the second case and *vice versa*. The sectors are thus conditioned by the first exposure respectively to respond and not to respond to the second exposure. Accordingly, the blue brush and the yellow brush both turn round through a right angle and manifest themselves conspicuously to the observer's vision.

The spectral characteristics: As stated above, the ability of the fovea to perceive polarisation is restricted to the blue-violet part of the spectrum. In other words, polarisation is detectable throughout the spectral range between 400 and 500 $m\mu$ but is unobservable in the region of greater wavelengths. A simple technique by which these facts can be demonstrated has been devised by the author. A brilliantly illuminated part of the sky (close to the sun) is viewed through the long slit-shaped opening between the two shutters of a window by the observer who

takes up a position at a suitable distance from the opening. Holding a diffraction grating before his eye, the observer can view the first-order spectrum produced by it and can direct his vision to any particular part of the spectrum and scan the entire spectrum from end to end. Insertion of a polaroid before the grating results in polarising the light appearing in the spectrum. Two brushes are then seen crossing each other, one of them being a bright brush and the other a dark brush. When the polaroid is rotated, both the brushes rotate together in the same direction as the polaroid. The brushes can be very clearly seen in the blue-violet sector of the spectrum, but not elsewhere in the other sectors of greater wavelengths.

That the polarisation of light is undetectable by the unaided vision if the wavelength of the light exceeds $500\text{ m}\mu$ also becomes evident when the observer makes use of a colour filter which completely cuts off all wavelengths less than $500\text{ m}\mu$ while freely transmitting greater wavelengths. Glass filters having such a spectral behaviour are commercially available and they appear of a golden-yellow colour by transmitted light. Viewing an extended source of light through such a filter with a polaroid placed in front which can be turned round in its own plane, critical examination fails to reveal any observable brushes in the field of view. *Per contra*, the use of a colour-filter that cuts out all wavelengths greater than $500\text{ m}\mu$ and transmits shorter wavelengths enormously facilitates the observation of the brushes. Instead of a blue brush crossed by an yellow brush, we have then a bright brush crossed by a dark brush, both appearing in a field exhibiting the colour of the transmitted light. The contrasts in respect of luminosity then manifested make the whole phenomenon very conspicuous. The axis of the bright brush is parallel to the direction of vibration in the polarised light, while the axis of the dark brush is transverse to that direction.

Techniques of observation: The use of a colour filter to eliminate the unwanted parts of the spectrum and of a polaroid to secure complete polarisation of the light in any desired azimuth makes further critical studies possible. Observations can then be made under controlled laboratory conditions and artificial light sources having the desired spectral characters can also be utilized. By such studies it can be established that, though restricted to the blue-violet sector of the spectrum, the ability to detect polarisation belongs to the same category of visual phenomena as the perception of light, form and colour and that it stands in the closest relationship with these perceptions. The difficulty which presents itself in the evanescent character of the phenomenon can be overcome by the adoption of a suitable technique. Holding the colour filter together with the polaroid in front of his eye, the observer should view an extended source of light. The polaroid should be held at first in a particular orientation and then smartly turned round in its own plane through a right angle. It should then be held in the new position for a little while and later turned back again to the original position. These movements may be repeated as often as desired. Immediately after the

polaroid is turned into a new orientation, the brushes are seen at their best, a bright brush along the direction of vibration in the transmitted light and a dark brush in the transverse direction. The brushes fade away soon, but they reappear in full strength in the new position when the polaroid is turned again through a right angle.

The extended sources of light needed for the study are most conveniently accessible out-of-doors, sunlit clouds being the most luminous. Next in order comes skylight, the brightness of which varies enormously with the part of the sky under observation, as also with the time of the day. In the vicinity of the sun, especially when it is covered by a thin haze, skylight can be extremely brilliant. Further away from the sun, the luminosity falls off rapidly. It also becomes very weak in the twilight hours. Indoor observations may also be made using screens which receive their light from open windows. If the screen employed is of the type used for projection work, consisting of a great number of tiny glass-balls embedded in a plastic sheet, a fairly high luminosity may be achieved. Other screens are, of course, less satisfactory. It should be remembered that the combination of a blue filter with a polaroid transmits only a very small part of white light. The need for a high intrinsic luminosity when an extended source of light is viewed through such a combination is obvious.

For observations indoors with monochromatic light the most suitable source is a powerful mercury arc lamp of the type used in street lighting. This should be enclosed in a box of suitable size which is provided with an exit window of sufficient area for the emergence of the light. A glass cell containing cuprammonium solution which covers the exit aperture makes an effective filter. It transmits the $\lambda 4358$ radiations and cuts out all longer wavelengths. The light emerging through the filter may be received on a ground-glass screen, the observations being made on the light emerging through it. Alternatively, the light may be received on an opaque diffusing screen, the surface of the latter being viewed by the observer at any convenient angle. This, of course, is a much less efficient source of light than the ground-glass screen which operates by transmission. No colour filter is necessary in either case, only the polaroid being held by the observer before his eye. By varying the distance of the ground-glass sheet or of the diffusing screen from the exit-aperture of the source, a very wide range of strength of the illumination may be obtained.

When the techniques of observation described above are made use of, it becomes immediately apparent that the perception of polarisation is only possible when the source under observation has a fairly high luminosity and that it becomes more and more difficult as the luminosity of the source is progressively diminished. Finally, a limit is reached below which the phenomenon cannot be perceived. These facts of observation make it evident that the perception of the brushes with polarised light is a phenomenon of a physiological nature. Its complete parallelism with the other aspects of the perception of light may be demonstrated with the aid of an ophthalmic chart of the usual kind consisting of

rows and columns of letters of various sizes printed in black on white cardboard. Viewed by the observer through a blue filter and a polaroid at the same levels of illumination, the visibility of the letters falls off in the same fashion.

Further striking evidence that the perception of polarised light is a physiological process is furnished by the following experiment. The observer should hold a blue filter and a polaroid before his eye and view a luminous field of adequate luminosity for a sufficient interval of time to allow the brushes seen at first completely to fade away. He should then suddenly remove the polaroid but allow the blue filter to remain in place. He will then see the brushes once again, but turned through a right angle. In other words, the fovea then perceives with enhanced brightness that part of the incident light which was cut off by the polaroid when it was in place before the observer's eye.

The origin of the Haidinger brushes: We may here comment upon the explanation of the brushes observed with polarised light which was long ago suggested by Helmholtz and received general acceptance, viz., that it is an effect arising from the dichroism of the material contained in the macular region of the retina. This explanation, if correct, would make the brushes a physical curiosity having no physiological significance. It is therefore appropriate here to point out that the explanation given by Helmholtz is wholly untenable. This becomes evident when we examine the assumptions on which that explanation is based and also when we compare its consequences with the actual facts of the case.

As has already been stressed, special techniques are necessary for the visual perception of polarised light to manifest itself in an impressive fashion. One of the essentials is the use of a colour filter which cuts out all light having a wavelength greater than $500\text{ m}\mu$ and transmits freely the region of the spectrum having shorter wavelengths. The luminosity of the field as seen through such a filter combined with a polaroid should also be adequate. When these requirements are satisfied, the field exhibits a bright brush running *parallel* to the direction of vibration of the light and a dark brush *transverse* to the direction of vibration. Employing the proper technique, we observe that the brush running transverse to the direction of vibration is completely dark.

If the facts of observation indicated above are to be explained on the assumption that the material of the retina in its foveal region has a radially symmetric structure which exhibits dichroism, it would be necessary for the absorption of light by the material to be effective and indeed *total* for optical vibrations along directions *transverse* to the radii of the structure and over the entire wavelength range between 400 and $500\text{ m}\mu$. Further, there should be no absorption at all for directions parallel to the radii of the structure. These assumptions are inadmissible for the following reasons. In the first place, the retina being a thin membrane and especially thin in the region of the fovea, the presence in it of sufficient absorbing material completely to block out the entire spectrum between 400 and $500\text{ m}\mu$ is scarcely possible. Indeed, our eyes would

then be unable to perceive the blue light of the spectrum. Another cogent objection is the known behaviour of fibrous materials dyed with organic dye-stuffs. In numerous cases where the dye-stuffs have elongated molecules, the dyed fibres do indeed display marked dichroism. But in all such cases, the strong absorption is manifested for directions of vibration *parallel* to the length of the fibres and not for directions *transverse* to them. It follows that the explanation suggested by Helmholtz for the appearance of the brushes is entirely mistaken.

It is well known that the retina exhibits a radially symmetric structure around the deepest part of the depression in it which is the fovea. The layers in the retina which elsewhere run parallel to its surface are tilted within the depression. As a consequence, the nerve fibres leading away from the bacillary layer run at an angle to the surface. These features appear as we move away from the centre of the fovea but are not noticeable outside the foveal depression. That the brushes observed with polarised light are a consequence of these features in the structure of the fovea is scarcely to be doubted.

That the brushes observed with polarised light are seen only within the limited spectral range in which the colour perceived is blue may be regarded as a demonstration that the material present in the retina which enables us to perceive light and colour in that spectral region is also responsible for the effects observed with polarised light. These effects accordingly enable us to infer some of the characteristics of that material. In the first place, its absorption of light should be limited to the blue sector of the spectrum. Then again, its molecules should possess an elongated structure and the absorption by them should be limited to directions parallel to the length of the molecules and relatively negligible in perpendicular directions. Further, these molecules should be disposed with radial symmetry in the fovea around its centre and should lie with their longest dimensions parallel to its radii, in other words, along the nerve-fibres which run at an angle to the surface (*see plate V*)*.

From the considerations set forth above, it would follow that except in regions close to the centre of the fovea, polarised light would be most strongly absorbed in the foveal region if its vibration direction is parallel to the radii of the structure and not absorbed at all if the vibration direction is perpendicular to the radii. Since perception of light is only possible as a consequence of the absorption of light by the materials present in the retina, it follows that with polarised light, we should observe a bright brush along its vibration direction and a dark brush running transversely to that direction. This, indeed, is what is actually observed.

It is thus evident that the brushes observed with polarised light furnish information of great value in regard to the identification of the material present in the retina, which enables us to perceive light and colour in the blue sector of the spectrum, and also in regard to the manner in which that material is distributed in the foveal region. We shall return to this topic in a later chapter.

*For plate V, see p. 591.

CHAPTER X

Visual acuity and its variations

We may begin by briefly recalling the facts of observation set out in Chapter V under the heading "Fluctuations of luminosity in visual fields". It was there stated that a diffusing screen which is uniform and is uniformly illuminated nevertheless appears to the observer viewing it from a distance to exhibit variations of luminosity over its area which alter from instant to instant and are seen to move about in a chaotic fashion. These variations of luminosity, however, exhibit certain recognisable characteristics which are different in different circumstances. They depend on the strength of the illumination and also on the distance of the observer from the screen. The spectral character of the light which illuminates the screen is also observed to play an important role in determining the characters of the observed phenomena.

It is evident that such fluctuations of luminosity would interfere with our perception of the details of any objects depicted on the screen which are recognisable by reason of differences in brightness or colour exhibited over their area. The extent of such interference with the visibility of the objects may also be expected to be influenced by the same circumstances as those which determine the characters of the fluctuations of luminosity. Observations show that these anticipations are completely in accord with the actual facts of the case.

For the study of visual acuity and its variations, the well-known Snellen test-charts of the type used by oculists are very convenient. Letters of various sizes printed in black on white card and arranged in rows and columns appear in these charts. The letters are of large size and few in number in the top rows and progressively diminish in size and increase in their number in the following rows. The sizes of the letters in the chart are such that when it is placed at a distance of 8 m from an observer with normal vision in a well-lighted room, he can read all the letters without difficulty or hesitation.

To exhibit the dependence of visual acuity on luminosity, the observations may be made in a chamber the admission of light into which can be controlled and varied over a great range with the aid of an iris-diaphragm covering a circular opening in a window which faces the sky. The test-chart should be placed as far away as possible from this opening, but facing it so that it is uniformly illuminated. The observer should also face the chart and can view it from any desired distance, commencing from the maximum permitted by the size of the room.

When the iris is fully open and the chart is therefore brightly illuminated, all the eight rows of letters on the chart can be read by the observer provided that he is not too far away from it. If the observer remains in a fixed position and the iris is then progressively closed down, the successive rows of letters disappear from sight one after another, commencing from the last row containing the smallest letters and proceeding upwards. Finally, when the opening of the iris is a minimum and the illumination of the chart is very feeble, even the rows at the top containing letters of large size are scarcely visible or recognisable. If at this stage, the observer moves towards the chart and comes closer to it, the sequence of changes is again observed, but in the reverse order. In other words, the rows of letters become visible one after another commencing from the rows of the larger letters at the top and moving downwards to the rows of smaller letters. Finally, when the observer is close to the chart, he can read all the letters, despite the weakness of the illumination.

Fluctuations and visual acuity: Attentive observation of the individual letters at various stages of the foregoing experiment reveals a phenomenon which may be described as a disintegration or break-up of the lines or curves which together make up a complete letter. In other words, only a part of the complete letter is visible and the other parts are not. At intervals, even the complete letter vanishes from sight and later reappears. These changes make it difficult to recognise and read the letters, and when they have proceeded far enough result in their obliteration. The lower the level of the illumination, the larger are the areas which pass out of sight. It is readily understood why in these circumstances, it is the smallest letters which first cease to be legible as the illumination is diminished and that they are followed later by the larger letters. Likewise, it is noticeable that the distance of the observer from the chart determines the size of the regions of disturbance. The closer he approaches to the chart, the smaller they become. When the regions are small enough, even the smallest letters on the chart become legible.

These facts are intelligible in the light of the opening remarks in this chapter. The ability to observe and recognise the details of any object under view depends on the existence of visible differences between the contiguous areas of the object in respect of brightness or other features, as also a reasonable measure of constancy in time of these differences. The observations set forth above demonstrate that the falling away of visual acuity with diminishing illumination is a consequence of the lack of such constancy. In other words, the perception of light is not continuous but is a fluctuating phenomenon, the magnitude and character of these fluctuations varying with the strength of the illumination and the distance of the observer from the object under view.

That the fluctuations of luminosity of the same nature as those described in Chapter V are the effective cause of the diminishing acuity of vision with decreasing illumination becomes even more clearly evident when we set the test-

chart side by side with a simple white screen so that they are illuminated similarly and observed from the same distance. It is then noticed that the parts of the chart in which the letters cannot be recognised exhibit the fluctuations of brightness much in the same manner as the smooth white screen. Further, even in the part of the chart where the letters can be read, local variations of brightness of the same nature and of the same magnitude as in the white screen are noticeable. In every case, the size of the patches of varying luminosity is comparable with the size of the letters which are just on the limit of visibility.

Instead of the Snellen charts, a white card on which rows of letters of different sizes following each other are printed may be used. The card may be held in the hand by the observer and read from the usual distance of distinct vision. We may, for example, have a card with ten rows in each of which all letters of the alphabet appear, the first row being 15 cm in length and the last only 3 cm long, the types being of correspondingly smaller sizes. In a brightly lit room, all the letters on the card are legible. But as the illumination is progressively reduced, the successive rows of letters commencing from the last go out of sight one after another, until finally even the first row becomes illegible. Simultaneously, it will be noticed that in the blank white spaces on either side of the region occupied by the letters, the card exhibits a fluctuating luminosity, the character of these fluctuations altering progressively as the illumination is reduced.

It is easy to demonstrate that the finer the detail which we wish to observe and recognise by our unaided vision, the stronger should be the illumination of the object under view. If, for example, we endeavour to read a page of ordinary print which has been miniaturised and reduced in size to a third or one-fourth of its normal dimensions, the lines of print on it will be found to be illegible even in a brightly-lighted room. But it is found that such a page when held in bright sunlight can be read easily enough.

Visual acuity and brightness contrast: The visibility of details in any object viewed by an observer is a consequence of the brightness or the colour of the object being different at different points in his field of view. The greater these differences are, the easier it is to recognise their existence, and it is a familiar experience that the closeness of the observer to the object and an increase in the strength of its illumination are both favourable to such recognition. Here again, we have another illustration of the role played by fluctuations of luminosity in the functioning of our visual perceptions. The effect of these fluctuations on the visibility of detail in the objects under view would evidently be greater, if the contrasts which permit of such visibility are relatively feeble. By increasing the strength of the illumination or by the observer approaching closer to the object, the fluctuations are rendered less effective and the visibility of the detail is thereby improved.

By way of illustrating the foregoing remarks and to reinforce them by actual observations, a Snellen test-chart was specially prepared which was similar to

those ordinarily made use of, but the letters, instead of being printed in black type, were filled up by hand using an ordinary graphite pencil. The letters then appear of a grey colour, the contrast between them and the white surface of the card being then much less than that exhibited by letters printed in black on white ground. When a Snellen chart thus prepared is set side by side with one of the usual kind, and the illumination of both is progressively reduced, they display a strikingly different behaviour. The chart with the grey lines becomes totally illegible at a level of illumination at which the black lines on the other chart can all be seen and the letters of the first four or five rows are quite distinctly readable. The fluctuations of luminosity are visible on both charts and their effectiveness in suppressing the visibility of the grey letters is recognisably the result of the low contrast between them and the background on which they have been placed.

Colour and the acuity of vision: A remarkable and highly significant relationship between the ability to perceive colour and the ability to perceive fine detail in a visual field emerges when the observations set out in the preceding paragraphs are made with monochromatic light instead of with ordinary daylight. Such observations demonstrate that, as in the case of white light, so also with monochromatic light, the fluctuations of luminosity in the visual field are effectively the origin of the observed dependence of visual acuity on the strength of the illumination. But they also show that *pari passu* with the fall in visual acuity as the strength of the illumination diminishes, there is a progressive falling off of the colour sensation excited by monochromatic light. The latter effect and its explanation have already been set out in Chapter IV on "The basic visual sensations". But what now emerges is that the perception of colour and visual acuity stand in the closest relationship to each other. As the sensation of colour becomes more pronounced, the acuity of vision is enhanced. *Vice-versa*, when the perception of colour becomes weaker, visual acuity also falls off. Finally, when the colour sensation ceases to be perceived, the visual acuity has also vanished.

An impressive demonstration of the statements made above may be given, using appropriate arrangements of the nature already described. A test-chart containing a series of rows of printed letters of progressively diminishing size is held by the observer in his hand and moved away from an area strongly illuminated by monochromatic light to a region in which the chart is much less strongly lit up. Viewing the chart in these circumstances, it is noticed that the successive rows of letters become illegible, commencing from those of smallest size and followed by those of larger size. Simultaneously, the colour of the illuminated chart exhibits a rapid change, beginning from a rich hue resembling that of the light-source as viewed directly and falling off to a much paler hue and progressively approaching an achromatic sensation. The experiment may be made with monochromatic light of various colours, viz., the yellow light of a sodium vapour-lamp, the green and the blue radiations of mercury-vapour isolated by appropriate colour-filters, and also with the light from a tungsten

filament lamp covered by a deep red filter. The rapid weakening of the colour sensation which accompanies the rapid diminution of visual acuity is noticeable in all cases. But the effect is particularly striking as exhibited by the blue-violet $\lambda 4358$ radiations of the mercury vapour-lamp.

That the variations of visual acuity with the strength of illumination over its entire range have their origin in the fluctuations of luminosity observed in the field of vision is readily established with the aid of monochromatic light-sources. The fluctuations are then distinctly more conspicuous than those observed with white light and are noticeable even at fairly high levels of intensity. The regions of the spectrum for which the visual acuity is low, including especially the blue, exhibit the fluctuations more conspicuously than those for which the visual acuity is high.

Binocular vision: The fluctuations of luminosity on a uniformly illuminated screen are more conspicuous when viewed with only one eye of the observer open (the other being closed), or *vice-versa*. This observation indicates that the fluctuations of luminosity as seen by the retinae of the two eyes are independent and the effect of binocular superposition is therefore to diminish their visibility. In the circumstances, it is not surprising to find that when a test-chart is viewed under reduced illumination, the visibility of the letters is noticeably improved by using both eyes instead of only one or the other.

Scintillating charts: Instead of letters of various sizes printed in black on a white background, we may employ charts in which the objects depicted are all similar and are arranged in regular geometric order. We may, for example, use charts exhibiting a pattern of white squares arranged in parallel rows and columns on a black background. It is useful to have a set of such charts in which the squares are of different sizes. They may be viewed by the observer from various distances and illuminated at different levels of brightness, and the visibility of the squares on the different charts may be compared with each other, and some quantitative results may be obtained. Some particularly interesting effects are noticed with the charts containing squares of rather small size, e.g., 5 mm, when they are illuminated with the light of a sodium vapour lamp at a fairly low level of brightness and viewed from such a distance that the squares can still be distinguished as separate entities. They are then observed to scintillate, showing large variations in intensity, the patterns of such luminosity moving over the chart from instant to instant. The charts containing the larger squares exhibit in similar circumstances some very curious phenomena, the individual squares changing their shape from instant to instant and showing irregular patterns of light and shade within their respective areas.

Visibility of fine detail: Of particular interest is the question, what is it that sets a limit to the ability of our eyes to perceive fine detail in any object? In considering

this question, we have also to take into account the nature of the object. Earlier in this chapter, we have already dealt with some particular cases, e.g., small letters in black type printed on white paper. The observations showed that an adequate strength of illumination is essential for their legibility. A somewhat similar case presents itself when we examine half-tone illustrations printed in black and white. It is the intention that the illustrations should present only gradations of light and shade to the eye of the observer. But when adequately illuminated, e.g., by direct sunlight, the mesh of even the finest half-tone screens is readily visible in the printed illustrations.

A slightly different situation arises when the object under examination is a transparency. We may take the typical example of screens woven with fine metallic wires interlacing each other. Such screens are commercially available and exhibit a remarkable uniformity in the diameters of the wires and in their spacing. Five such screens have been examined by the author, the spacing of the wire-mesh being respectively 0.85, 0.52, 0.26, 0.22 and 0.18 mm. When held at the usual distance of distinct vision and viewed against the bright sky, the two most widely spaced meshes are quite clearly visible. But the visibility is much less with the other three, the last of the series being particularly difficult. In every case, the visibility falls off as the screen is moved further away from the observer, the maximum distance beyond which the visibility vanishes being the greatest for the first of the series and progressively less for the others. It is found also that the visibility depends notably on the illumination of the background against which the mesh is viewed, the minimum necessary increasing as the spacing of the wires is smaller. Even the coarsest mesh of the five ceases to be visible when held at the usual distance of distinct vision, if the background illumination is below a certain limit.

A rather searching test of visual acuity is provided by the "BMC Fine mesh" made by the firm Buckbee Mears of Saint Paul, Minnesota. This is a thin film which exhibits under a magnifying lens a network of dark lines spaced a tenth of a mm apart and crossing each other at right angles. For the mesh to be visible to the unaided eye, it is found necessary to hold it against a brilliantly illuminated background.

CHAPTER XI

Vision in dim light

There is an immense disparity between the illumination which reaches the Earth in daytime from the Sun and the light received from various sources in the sky on a clear but moonless night. The former is roughly about a thousand million times brighter than the latter. Between these extremes is the light of the full moon which may be put as roughly half-a-millionth part of the light of the noonday sun. Twilight, the duration of which in the tropics is about an hour, permits of a comfortable transition from the brilliance of sunlight to the dimness of starlight, in other words allows human vision to adjust itself naturally to the enormously reduced intensity. It also permits of a leisurely observation of the changes in the characters of the visual perception of light which accompany this reduction.

Very readily noticeable changes appear in our visual perceptions in dim light; firstly, the very low visual acuity and secondly, the weakness or even total disappearance of the sense of colour. These changes are essentially progressive in their nature, becoming more and more obvious as the level of illumination falls off. In the earlier chapters of this book, it has been shown that such changes are necessary consequences of the corpuscular nature of light. No special hypotheses or assumptions are needed to account for them.

The idea that human vision is of two kinds designated respectively as photopic vision and scotopic vision arose originally as an explanation of the disease or abnormal condition known as night-blindness. It gained strength from the anatomical finding that there are two kinds of structures in the retina, now known familiarly as the rods and the cones which were identified as the visual receptors. It was an easy step to recognise the rods as the receptors for dim light and the cones as the receptors for bright light. A further step was to assume that the rods enable us to perceive light but without colour, whereas the cones enable us to perceive both light and colour.

We shall later in this book have occasion to comment on these and other aspects of the duplicity theory of vision. In the present chapter, we shall confine ourselves to setting out the observational evidence that points to the conclusion that human vision is of one kind only at all levels of illumination.

As has been remarked above, the differences between vision in bright light and vision in dim light are of a progressive nature and it is not possible to set definite limits which would require us to recognise two different categories of perception. This is particularly evident from the studies of visual acuity and its variations

described in the preceding chapter. The strength of illumination needed for any particular visual task is determined by the nature of the task. If the task is particularly difficult, brilliant light is needed. If the task is easy, much less illumination is sufficient. Hence, the differences in visual acuity cannot possibly furnish any support for the idea that vision is of two different kinds.

The position is very similar in regard to the perception of colour. We have indeed remarked upon the remarkable parallelism which exists between the variations in visual acuity and in colour perception produced by lowering or raising the level of illumination. Colour is vividly perceived in bright light and it fades away quite gradually as the light becomes feebler. Here again, there is no basis for the assumption that we have two kinds of vision, one in which we have both light and colour and another in which we have light but no colour.

The credence which the duplicity theory of vision obtained is largely based on the supposition that the rods and cones correspond to two different kinds of perception. As against this, we have only to point out that in the foveal region of the retina, the anatomist finds only cones and no rods. Nevertheless, the characteristic differences between vision in bright light and vision in dim light, viz., the lowered visual acuity and the enfeebled perception of colour are very clearly manifested in foveal vision. From this, it may properly be inferred that the rod-cone dualism is altogether irrelevant in this context.

The clearest proof that we are concerned with only one kind of vision at all levels of illumination is forthcoming from a study of the spectrum of white light commencing from ordinary or daylight levels and carried down to the lowest levels of illumination at which it is possible for vision to function. There are indeed noteworthy changes in the observed features of the spectrum as has already been remarked in Chapter VI. But there is a feature common to all levels, namely the role played by the green sector of the spectrum, the limits of which may be put as between 500 and 560 $m\mu$ in wavelength. This sector may properly be described as the principal feature in the spectrum of white light. It is a region in which the luminous efficiency is high. As we pass from bright light to dim light, the parts of the spectrum which are of both greater and lesser wavelengths, viz., the red, orange and yellow on one side and the violet, indigo and blue on the other fall off in their luminous efficiency and ultimately disappear from sight. But the green sector survives even in the dimmest light and is indeed the only part of the spectrum which then functions in vision. It is thereby made evident that a differentiation between photopic and scotopic vision is wholly unjustified.

There are several different techniques which may be adopted to enable us to observe the changes in the spectrum of white light as the level of its brightness is progressively reduced to the minimum. They all yield the same result. We shall describe them in the order of their simplicity, beginning with that which is the least sophisticated and ending up with that which makes use of instruments and artificial light sources.

Observations with colour-filters: The observer takes a seat in a completely darkened room at a distance of about 5 m from a white screen which he faces. The light of the sky enters the room and falls on the screen through an aperture covered by an iris diaphragm the diameter of which can be varied over a great range of values from 20 cm down to a few mm. The screen of which the illumination is thus controlled is viewed by the observer through one or another of a set of suitably chosen colour-filters placed before his eye. The observations are made at a series of levels of brightness commencing from the lowest possible at which the illumination of the screen is so feeble that it remains invisible to the observer until after a prolonged stay by him in complete darkness. The results of the observations are quite different for the different colour-filters and indicate how the luminous efficiency of the spectrum in its various regions alters with the level of the illumination of the screen.

With the illumination of the screen at its lowest level, the difference between the effects observed with colour-filters which transmit the green sector of the spectrum and with those which do not is extremely striking. The screen remains invisible when viewed through filters which transmit only the red or the blue sectors of the spectrum and are opaque to the green sector. Likewise, a colour-filter of gelatine dyed with magenta which transmits both red and blue light freely but cuts out the green appears completely opaque. On the other hand, a yellow filter which cuts out the blue but freely transmits green and the rest of the spectrum appears quite transparent and does not observably diminish the brightness of the screen. The measure of the transparency of a filter to green light is also a measure of the brightness of the screen as seen through it.

What has been stated above represents also what is observed at levels of illumination considerably higher than the lowest. Step by step, however, as the iris diaphragm is opened and more light falls on the screen, the complete extinction of the parts of the spectrum other than the green is replaced by a weak transmission. But at all stages, the green sector continues to exhibit a luminous efficiency far greater than those of the other regions of the spectrum. It is also notably superior to them in respect of the acuity of vision.

The spectrum of twilight: The light of the sky in day-time owes its origin to the scattering or diffusion of the rays of the sun by the atmosphere and the dust or other small particles present in it. As is to be expected in the circumstances, the brightness of skylight depends greatly on the time of the day and on the part of the sky under observation. Skylight is, in general, extremely brilliant in the immediate vicinity of the sun and much weaker in directions remote therefrom. These differences manifest themselves very clearly in the spectrum of skylight as viewed through a pocket spectroscope. Great brilliancy is accompanied by an increase of the visible length of the spectrum at both ends, as also by an increased prominence of the yellow sector. *Per contra*, a readily visible contraction of the

spectrum at both ends and a noticeable weakening of the yellow are observed when the skylight is of diminished brightness.

As the sun moves down towards the horizon before it sets, its light has to traverse increasingly greater distances through the atmosphere and is much reduced in its brightness by diffusion. The light of the sky above the observer is much enfeebled as the result. When the sun goes below the horizon, the shadow of the earth moves upwards and only the upper layers of the atmosphere receive the light of the sun directly. Since these layers fall off in density with increasing height, there is a rapid diminution of the strength of skylight. The effect of this can be readily followed by observations of various parts of the sky through a pocket spectroscope. The red, orange and yellow disappear completely from the spectrum, while the colours at the other end are also much enfeebled. But the green survives and continues to be seen until twilight has itself disappeared.

A more satisfactory procedure for the study of the spectrum of twilight will now be described. The observer sits in his room 2 m away from a window which faces north or east and is provided with wooden shutters. These shutters when fully open allow a clear view of the sky. But only a vertical slit a few mm wide is allowed to remain open between them, while the shutters of all the other windows are closed, thereby making the room completely dark. The observer views the slit through a replica-grating held before his eye, fixing his attention on its first-order diffraction spectrum. Since the spectrum is an image of the slit formed by diffraction, it has the full length of the slit which may be a metre or more. A spectrum of this length is seen running through the field of view from end to end. It thereby becomes possible to study the spectrum as seen both by foveal vision and by peripheral vision over a wide range of visual angles.

The observations are best made when the sky is quite clear and there is no moon, so that when twilight has ended, the sky is as dark as it can be. There is a large progressive fall during this period in the intensity of the light which finds entry through the slit and of the resulting diffraction spectrum. But since the room is completely dark, the sensitivity of the observer's eye to faint light improves greatly during the same period. He therefore finds no difficulty in watching the spectrum and the changes which appear in it until it becomes extremely weak. It is found useful for the observer to have at his disposal three colour-filters, respectively red, blue and yellow, which can be quickly inserted between the eye and the diffraction grating as and when desired and which can also be used for a direct observation of the slit through the filter at intervals during the series of observations.

At the start of the observations, the spectrum presents much the same appearance as in daytime. At the end of the sequence, all that is seen of the spectrum is a long strip of light with no recognisable colour but in the same position as the green sector of the spectrum seen at the beginning. That all other parts of the spectrum have ceased to be observable is readily established with the aid of the red and blue filters. Either of these filters when inserted before the eye

(with or without the diffraction-grating) results in a complete cut-off of all the visible light. On the other hand, the insertion of the yellow filter which has no sensible absorption in the green sector has no effect. In other words, what is actually visible is only the green of the spectrum.

The technique of study described above has some valuable features. The brilliance of the spectrum produced by the replica-grating and the adequate resolution and dispersion which it provides enables the spectrum to be carefully examined and the entire sequence of changes in colour and luminosity to be followed continuously over a great range of brightness. As these changes have, for the most part, been described earlier in detail using other methods of observation, it is not necessary here to traverse the same ground. The specially noteworthy feature at the lower levels of illumination is the progressive contraction and final disappearance of the short-wave region of the spectrum which normally exhibits the colour sequence of blue, indigo and violet. Another useful feature of the technique is that it enables the spectrum as it manifests itself to the peripheral regions of the retina to be examined over the same extended range of luminosity as foveal vision. No noticeable difference has been observed.

The faintest observable spectrum: A simple technique has already been described in Chapter VI which enables the spectrum of a source of white light to be viewed at various levels of brightness, ranging from one of great brilliance in which the yellow sector is the dominant feature in the spectrum down to levels at which all other regions of the spectrum appear much enfeebled in comparison with the middle or green sector which is then its most conspicuous part. A few simple modifications of the same technique enable the observations to be carried down to the lowest levels of brightness at which the spectrum itself ceases to be visible. The two modifications necessary are, firstly an arrangement by which the flux of light finding entry into the slit of the spectrograph can be progressively reduced to the extent necessary, and secondly, an arrangement which secures that the observer viewing the spectrum on the ground-glass-screen of the instrument remains in complete darkness so that his vision functions with the maximum sensitivity.

The source of light employed is the same as before, viz., a coiled-coiled tungsten-filament-lamp kept cool by a fan blowing air on it and emitting a brilliant white light. This is placed in an annexe separate from the completely darkened room in which the spectrograph and the observer are located, and at a distance of 5 m from the instrument. The collimator is directed towards the source of light and a screen prevents the entry of light into the observing room except through an aperture 5 cm in diameter covered by a ground-glass sheet which diffuses the light forwards. The distance between this sheet and the slit of the spectrograph being 4 m, the diffusion results in the flux of light entering the instrument being greatly diminished. A further diminution is effected by an iris-diaphragm which covers the aperture and enables it to be reduced from

a maximum diameter of 5 cm down to 3 cm. The slit-width of the spectrometer can also be varied from 1 mm down to a few hundredths of a mm.

With these arrangements and a dark hood screening his eyes from stray light, the observer can watch the whole sequences of changes produced by closing down the iris-diaphragm when the slit-width is at a minimum. He then observes that the only part of the spectrum which survives till the last and then passes out of sight is the green sector of the spectrum, the wavelength limits of which can be put at 500 and 560 m μ .

Observations with mercury lamps: A very instructive modification of the arrangements described above is to replace the tungsten-filament lamp by a mercury-vapour lamp enclosed in a bulb of the type which is commercially available. With such a lamp at a distance of 5 m from the slit of the collimator and with the slit-width set at a tenth of a mm, all the strong lines of the mercury arc appear on the ground-glass screen of the spectrograph and can be viewed through a magnifier. It is noteworthy that the two so-called yellow lines λ 5790 and λ 5770 are recognisably different in their colour, the former being distinctly orange-yellow and the latter distinctly greenish-yellow. When a plate of ground-glass is put in and covers the aperture through which the light of the mercury lamp has to pass before it reaches the spectrograph, there is a great diminution in the brightness of the spectrum. The lines λ 4358 and λ 4046, and the faint continuous spectrum disappear, while the yellow lines λ 5790–5770 become much weaker than the green λ 5461. The weak λ 4916 also ceases to be visible. When the iris-diaphragm covering the aperture is progressively closed down, further changes appear in the spectrum. The yellow lines become fainter and fainter and finally disappear. But the green line λ 5461 continues to be visible as the sole surviving feature of the spectrum till the very end.

Very useful also are the observations made with a mercury-vapour lamp of the same kind but which exhibits a strong continuous spectrum extending over the entire range from the red to the violet and overlying it also the lines of the mercury arc spectrum. With this lamp, the changes in the continuous spectrum can be followed, besides those of the bright lines in the spectrum. The red part of the continuous spectrum as well as its blue part disappear along with the lines λ 4916, λ 4358 and λ 4046 when the ground-glass plate is put in to cover the light of the lamp as it emerges from the aperture before it can reach the spectrograph. What then remains are the two yellow lines λ 5790–5770, the green line λ 5461, and the part of the continuum appearing in the green sector of the spectrum. As the aperture through which the light emerges is progressively closed down, the yellow lines rapidly become weaker and disappear. But the green line λ 5461 and the continuum which accompanies it continue to be visible as the sole surviving parts of the spectrum.

CHAPTER XII

The night-sky

The spectacle presented to us every clear night of the dome of the sky studded with stars has been the inspiration for the systematic explorations of space with the aid of powerful telescopes which have revealed to science the immensity of the cosmos. What we perceive of the Universe without such instrumental aid is evidently but a small part of the gigantic whole. Nevertheless, the role played by our visual faculties in enabling us to perceive at least what lies nearest to us in the vast expanses of space is of the highest interest and significance. It is clearly worthy of the closest study.

The investigations on vision in dim light described in the preceding chapter suggested to the author that a simple visual examination of the sky at night through various colour-filters might yield results of interest. This has indeed proved to be the case. The very striking fact has emerged from such observations that the night-sky as viewed through a colour-filter which transmits the green part of the spectrum freely does not differ noticeably in its appearance from what is seen without a filter, even though the filter cuts out the rest of the spectrum. *Per contra*, a filter which absorbs the green of the spectrum but freely transmits all the rest obscures the view of the night-sky more or less completely when held by the observer before his eyes. A filter of the first kind is provided by a gelatine film on glass dyed with lissamine green. It cuts out the red, orange and yellow and much weakens the blue in the spectrum. A filter of the second kind is provided by a gelatine film on glass heavily dyed with magenta. This cuts out the green completely but transmits the red and the blue regions of the spectrum. What these observations signify is that at the low levels of illumination presented by the night-sky, the green of the spectrum is the only part of it which has a luminous efficiency of significant magnitude, while the rest of the spectrum is, by comparison, of negligible importance.

It follows from what has been stated that the light received at ground level from the night-sky and which illuminates the landscape would exhibit the same characteristics, in other words, that the only significant part of it is that comprised in the green sector of the spectrum. This inference is confirmed by viewing the landscape in such circumstances through various colour-filters. We may describe the situation in the following manner. If an observer is walking along a path having only the dim light from the star-studded sky to guide his footsteps, he would have no difficulty whatever in keeping to the path if he wears green or

yellow spectacles. But if he wears glasses of any colour, such as red or blue which excludes the green part of the spectrum, he would find himself walking in darkness. Such an experience would help him to realise that vision in bright light and in dim light are not essentially of a different nature.

The light of the night-sky belongs to two distinct categories, namely that derived respectively from terrestrial and extra-terrestrial sources. To the latter class belong the individual stars which are perceived by an observer as points of light, ranging in brightness from the most luminous to those which are so faint as to be barely visible. We have also light from the immense numbers of stars present in the Galaxy which the eye is unable to perceive as individual sources of light but which are revealed by the diffuse luminosity of the sky which they produce. The familiar manifestation known as the Milky way is the most conspicuous exhibition of the luminosity thus arising, and can be seen as a great belt running round the sky. The zodiacal light which is conspicuous in certain regions of the sky and at certain times also makes an important contribution to the light of the night-sky. Amongst the sources of terrestrial origin, should be mentioned the phenomenon known as the air-glow. Much more disturbing is the atmospheric diffusion arising from the illumination of towns and cities at night by electric lights. This is indeed so disturbing that the author found it necessary to move out of Bangalore to various places ten or twenty or thirty miles away to make a critical study of the features of the night-sky.

An observer holding a colour-filter before his eyes can readily note the difference which the filter makes to the appearance or the visibility of particular features in the night-sky. Such observations make it evident that even the brightest stars are very weak in comparison with the artificial light-sources with which we are familiar. Whereas even distant street-lights can be seen through a filter of red glass and exhibit the vivid colour to be expected, the effect of its interposition before the eye is a blackout of the night-sky, a blackout which extends even to the brightest stars, if the filter transmits only the extreme red end of the spectrum. Filters of red glass of which the cut-off is at $600\text{ m}\mu$ permit some of the brighter stars to be seen through them, but the night-sky is for the most part excluded from vision.

Sheets of blue glass of the kind used as window panes are commercially available. They freely transmit light of wavelengths less than $480\text{ m}\mu$ and exhibit strong absorption bands in the yellow and red sectors of the spectrum. But the absorption of the green sector by such a plate is far from being complete. But by holding four such plates together, it is possible to extinguish the green completely without greatly weakening the blue part of the spectrum. When held before the eye, the combination of four plates results in a blackout of the night-sky, only a few of the brightest stars remaining visible. Observing the sky successively through one, two, three and four plates, it becomes evident that it is the partial transmission of the green in each case which enables the fainter stars to be seen, the blue of the spectrum contributing but little to their visibility. It may be

remarked that a red star, e.g., Betelgeuse goes out of sight earlier in the sequence than other bright stars such as Sirius and Rigel.

A colour-filter which is of a pale yellow hue by transmitted light and completely cuts out all wavelengths less than $480\text{ m}\mu$ when held before the eye of an observer viewing the night-sky appears both colourless and quite transparent. In other words, the extinction by it of the blue part of the spectrum is without effect on the observed luminosity of the objects seen through it. But a glass filter of a deeper yellow colour which has a cut-off at $510\text{ m}\mu$ is distinctly inferior to it in respect of transparency. A filter of orange hue which has a cut-off at $540\text{ m}\mu$ results in a drastic reduction of luminosity when the night-sky is viewed through it. As these two filters absorb appreciable fractions of the green sector of the spectrum, their behaviour is in accord with expectation.

The sheets of green glass which are commercially available are not completely transparent to the green sector of the spectrum and this reveals itself when the night-sky is viewed through a sheet of such glass. Greatly superior to it in this respect are filters of gelatine dyed green by appropriate dye-stuffs. For example, a filter prepared with lissamine green which is completely opaque to the yellow, orange and red sectors of the spectrum nevertheless appears both colourless and transparent when the night-sky is viewed through it. Very similar is the behaviour of gelatine filters which appear of a blue-green colour by transmitted light in daytime and which, while completely excluding the red, orange and yellow sectors of the spectrum, freely transmit the green and blue sectors. Such filters may be readily prepared by staining gelatine films with an appropriate dye-stuff, e.g., cyanin or disulphine blue. Held against the night-sky, these filters appear both colourless and transparent.

The spectrum of the night-sky: A very convenient arrangement for visual study of the spectrum of skylight is for an observer to take his seat on the floor beneath the dome of an observatory of which the shutters are nearly but not completely closed, leaving a narrow slit a few cm in width open between them. The slit extends from the zenith up to the foot of the dome, thus covering a wide range of visual angles. Holding a replica grating before his eye, the observer views the slit, fixing his attention on one of the two first-order diffraction spectra which appear projected on the interior surface of the dome, running parallel to the slit through which the light of sky finds entry, the spectra appearing respectively on the two sides of the slit. The dome can, of course, be turned round to face any desired part of the sky. As the dome and walls of the observatory exclude the admission of light except through the slit, the observer finds himself in practically complete darkness, and this greatly facilitates his study of the spectrum. The arrangement can be used for observations of the spectrum of skylight during the twilight hours or at night after the cessation of twilight. In the latter case, the light finding entry through the slit is very dim provided there is no moon and the sky is clear. But the observer being then in total darkness, his eyes are very sensitive to faint light, and

there is no difficulty in viewing the spectrum and taking note of its characteristics. It does not exhibit an observable colour and appears as a strip of light much narrower than the spectrum of skylight as seen before or immediately after sunset. This is to be expected since only the green sector of the spectrum is perceived in these circumstances. The absence of the other parts of the spectrum can be readily checked with the aid of colour-filters which transmit red or blue light. When such a filter is inserted between the diffraction grating and the observer's eye, the diffracted image of the slit in the dome is totally extinguished.

On clear moonless nights, when a particularly bright star can be glimpsed through the slit, its individual spectrum can be seen as a bright streak of colour running across the strip of light which is the diffracted image of the slit as seen by the observer. But the streak does not, as a rule, extend visibly beyond the green of the spectrum. Fainter streaks can occasionally be glimpsed which represent the spectra of individual stars. Indeed, at least in theory, the entire diffracted image of the slit is made up of the spectra of the individual stars of which the light reaches the eye of the observer with his grating. But in practice, these are either too faint to be perceived individually or else are lost in the spectrum of the background illumination.

The effect of the presence of moonlight on the observed spectrum of the night-sky can be readily studied with the same arrangements. The principal effect is an increased brightness, such increase being dependent on the phase of the moon and on the particular part of the sky under observation. When the moon is at least half-full, the added luminosity due to scattered moonlight has a perceptible effect on the character of the spectrum of the night-sky. No colour is observed, but the width of the strip of light seen as the spectrum is noticeably enhanced, and its extinction by the introduction of a red or a blue filter before the diffraction grating ceases to be total, especially in the case of the blue filter.

Visibility of the stars: The lucid stars, in other words, those which can be perceived by the unaided vision in the most favourable circumstances are a few thousands in number. The very bright stars are relatively few and those which are less bright become progressively more numerous as they go down in the scale of luminosity. Using a pair of binoculars of which the objectives have an aperture of 5 cm each, the number of stars which are visible shows a great increase. The brilliancy of the stars which can be seen without optical aid is also greatly enhanced. From these facts of observation, we may infer that the factor which limits the visibility of stars to a relatively few is their low luminosity. In other words, the vast majority of the stars are not seen by reason of the fact that the light they emit and which reaches us is far too weak to excite a persistent sensation.

A convincing demonstration of the correctness of the foregoing inference is furnished by observations of the night-sky through a pair of polaroid sheets of adequate size (at least 10 cm square) mounted in circular frames so that they can be held covering both the eyes of the observer and rotated with respect to each

other. A protractor with an index attached to the frames enables the angle of setting of the polaroids with respect to each other to be read off at a glance. When the polaroids are in a parallel setting, the brightness of the transmitted light is the maximum: as the setting is altered, the transmission progressively diminishes and becomes zero when the polaroids are in the crossed position. In the parallel setting, the well-known constellations of bright stars, e.g., Canis Major, Orion and Ursa Major, can be seen and present their usual appearance. But as the setting is altered, the stars pass out of sight in succession, the fainter ones first, followed by the others and finally also by the brightest stars. During this operation, the constellation becomes unrecognisable and finally disappears altogether.

There is a finite range of settings, one on either side of the crossed position, within which each star remains invisible. This range is greatest for the fainter stars, and smallest but nevertheless finite and measurable for the bright stars such as Sirius, Rigel and Betelgeuse. The range of settings within which a star remains out of sight is an inverse measure of its brightness. It is worthy of note that the background illumination of the sky does not stand in the way of making the observations. For, the background is reduced in its brightness in the same ratio as the star under observation when the polaroids are rotated with respect to each other.

Fluctuations of starlight: The corpuscular nature of light necessarily plays a highly important role in our visual perception of the stars. It is obvious that it would not be possible to perceive a star steadily as a point-source of light unless the stream of light-corpuscles reaching the particular spot on the retina is continuous and of sufficient strength. Failing this, we can only expect to perceive the star by fits and starts; in other words, it would present a fluctuating luminosity. Such an effect would be exhibited most clearly by the fainter stars and would be less and less evident as the star goes up in the scale of luminosity. It should be remarked that the fluctuations in the luminosity of the stars referred to here are altogether different in their characteristic features from the well-known phenomenon of the scintillation of the stars. The latter phenomenon has its origin in the local variations of the refractivity of the earth's atmosphere. The brighter stars exhibit that effect to the same extent as the feebler ones and it may indeed be more readily noticeable with the brighter stars than with the fainter ones. The scintillations of atmospheric origin would naturally depend greatly in their frequency and magnitude on the condition of the atmosphere, and in particular circumstances they may be extremely rapid. Further, the position of the star, viz., whether it is nearer the horizon or the zenith is found to have a noteworthy influence. In all these respects, the fluctuations of starlight with which we are here concerned differ from the familiar phenomenon of the twinkling of the stars. Hence, the attentive observer can easily distinguish between them and recognise the nature of the effects which are noticed by him.

Actually, there is no difficulty whatever in perceiving and recognising the fluctuations in brightness of the fainter stars which arise by reason of their low luminosity taken in conjunction with the corpuscular nature of light. Observations of it are best made with stars which are high up in the sky and on clear calm nights when the brighter stars in that vicinity do not exhibit the variations in luminosity of atmospheric origin in a conspicuous manner. The fluctuating brightness of the fainter stars is most clearly evident when two or more faint stars which are fairly close together are viewed by the observer and their relative luminosities are kept under constant comparison. It will be found that these are constantly changing. A very convenient set of stars for such observations is the well-known star-group Pleiades. But there are many other star-groups which can serve just as well.

The milky way: The stars perceived by our unaided vision all belong to the Galaxy in which our Sun is but one amongst a vast number of such luminaries. We perceive a star as an individual speck of light in the sky by reason of its luminosity being sufficiently great and its distance from us sufficiently small to ensure that the luminous flux from it entering the pupil of the observer's eye and reaching the retina is sufficient to give rise to a persistent sensation. The stars which satisfy this condition are an exceedingly small fraction of the great number constituting the Galaxy. It might seem at first sight that these circumstances would result in the existence of the Galaxy for ever remaining outside the field of direct visual perception. There are however certain circumstances which lead us to modify this conclusion.

We have, in the first place, to take note of the characteristics of human vision at low levels of illumination. These are very well illustrated by holding a wire-mesh at the distance of distinct vision and viewing it against a bright background of which the illumination can be progressively reduced. When the illumination is adequate, the apertures in the mesh through which light can pass are perceived well-defined and clearly separated from each other. As the illumination is progressively reduced, a stage is reached when the individual apertures cease to be visible and the entire mesh appears as a uniform field of illumination, but exhibiting noticeable fluctuations in brightness over its area. The latter phenomenon becomes more and more conspicuous as the illumination is further lowered.

What has been stated above is entirely relevant to the visual perception of the field of stars appearing in the sky at night. The brighter stars may be perceived as individual points of light. But the great majority are much too feeble to be thus perceived. In these circumstances, the physiological characteristics of vision result in the field under observation appearing as an area of continuous illumination which however exhibits recognisable fluctuations of luminosity. The general illumination of the sky on a clear night, apart from disturbances of terrestrial origin mentioned earlier, evidently arises in this manner. Its brightness

would naturally depend on the density of the stars in the part of the field under observation. The vast majority of the stars in the Galaxy are, owing to their great distances from us, of extremely low luminosities. But this is set off by the great numbers present at such distances. Hence, the luminosity of the sky which they produce is sufficient to be readily observable. That this luminosity is particularly conspicuous in certain regions is readily understood from the general form of the Galaxy as a flattened spiral and the position of the Sun at a point considerably removed from its centre.

As is to be expected in view of the extreme feebleness of the light of the Milky way, it is completely blacked out when a filter of red or blue glass is held by the observer before his eyes. *Per contra*, the Milky way is seen with undiminished brightness through any colour-filter which does not sensibly absorb the green sector of the spectrum. The fluctuating character of the light of the Milky way will be evident to an observer who watches it attentively. This results in the shimmering appearance which is its characteristic feature.

CHAPTER XIII

Adaptation of vision to dim light

In the two preceding chapters, we dealt with the functioning of human vision at low levels of brightness. It emerged that the differences between vision in bright light and in dim light are not of such a nature as to place them in two distinct categories; *per contra*, they have features in common which make it evident that human vision is of one kind only and not of two kinds as has been surmised or believed hitherto. In view, however, of the enormous range of levels of brightness in which our eyes can function, it is not surprising that certain differences in the manner of such functioning are noticeable over this range. These differences have been discussed in considerable detail earlier in the present work.

In the present chapter we shall consider the phenomena which comes to notice when there is a sudden transition from bright light to dim light, instead of the slow and progressive change which occurs in the twilight period between day and night. The tasks which the visual mechanism is called upon to perform at high and at low levels of illumination respectively are very different. The stream of radiant energy entering the eye in the latter case is a mere trickle compared with the massive flow in the former. That the physiological mechanism would take time to adjust itself so that it can perform satisfactorily in dim light is only to be expected. This period is usually referred to as that needed for adaptation of vision to the altered level of illumination. The nature of this process clearly needs elucidation.

It is a matter of familiar experience that an observer who has been out-of-doors and enters a dimly-lit room finds at first that he is unable to perceive the objects in the room and has the feeling of being in a dark chamber. Later, his vision improves and there is a progressive increase in the apparent brightness of the walls of the room and of the objects located in it. It is these features which characterise the process of adaptation. A convenient procedure for studying them in detail is to place a screen of white plastic material of suitable size, say a square metre, in a completely darkened room into which, however, skylight enters through an opening of adjustable size and falls upon the screen. The observer takes up a position at a suitable distance from the screen, say 5 m, from which he can keep it in view. The opening through which the light finds entry being an iris-diaphragm, the illumination of the screen can be varied at will over a wide range of values.

If the aperture of the iris is set at the minimum and the screen is therefore only

feebly illuminated, the observer entering the darkened room from an adjoining room which is brightly lit will at first fail to perceive the screen, and some minutes have to elapse before it becomes visible to him. This period is much prolonged if the observer before entering the darkened room has been out in the open and has exposed his eyes to light of high intensity. *Per contra*, the period is much shortened if the illumination of the screen by the opening in the iris is set at a fairly high level. Indeed, when the iris is fully open and the screen is brightly illuminated, it would become visible to the observer immediately. With the same arrangements, it is possible also for the observer to follow the progressive brightening of the screen during the period of adaptation.

An insight into the nature of the process of adaptation is obtained by placing an ophthalmic test-chart of the usual kind alongside the screen under observation so that they are equally illuminated. This illumination may be such that an observer entering the room from outside can perceive both the screen and the ophthalmic chart at once but at first only feebly. In the course of the next few minutes, both the screen and the chart brighten up. Whereas at the beginning, the letters on the chart are totally indistinguishable, they come into view in a regular sequence, the letters of the larger sizes first and those of smaller sizes later, until when the adaptation is complete, they can all be seen as clearly as could be expected. During the same period, the fluctuations of luminosity noticeable on the screen which at first are highly pronounced later become progressively more subdued. The visual appearance of the screen and of the chart at the various stages of adaptation are thus closely related to each other.

If during the period of adaptation when the screen and the chart have not attained their maximum brightness, the observer who has been viewing them from a distance moves forward and comes quite close to them, a remarkable effect is noticed. The screen suddenly brightens up and the fluctuations of luminosity on it cease to be observable. Simultaneously also, the chart brightens up and all the letters on the chart (including even those of the smallest sizes) become perfectly clear and legible. The increase in visual acuity which occurs when the observer comes close to the chart is extremely rapid and is evidently the effect of the greatly increased brightness of the chart in the same circumstances.

If the illumination of the screen and of the chart are initially at a very low level, they are both invisible to the observer when he first enters the darkened chamber. Several minutes have to elapse before they become visible. The screen when first seen then shows large and very conspicuous fluctuations of luminosity over its area, and the chart also behaves similarly, no trace of the letters printed on it being noticeable. Later, the screen brightens up and the fluctuations of brightness over its area become more subdued. The letters of largest size on the chart also become distinguishable. If the observer comes very close to the screen and the chart, they brighten up and the letters on the chart become suddenly visible in the same manner as previously described.

The foregoing observations make it evident that the two features which are

characteristic of the process of visual adaptation, viz., the initial failure to perceive very feeble light and its subsequent perception with a progressively increasing brightness have a common origin and are indeed only different phases of the same phenomenon. The nature of that phenomenon is revealed by the progressive changes in the character of the fluctuations of luminosity visible on the screen and the progressive increase of visual acuity during the period of adaptation. These observations make it evident that the effect of exposure of the eyes to bright light is to diminish the response of the receptors of vision in the retina to an extent determined by the strength of such light and the duration of the exposure. This weakening reduces the ability to perceive light in general and particularly the ability to perceive light of low intensity. In the latter case, the weakening may be such as to make perception of feeble light impossible. Given time, however, the receptors recover from this state which may be described as one of nervous fatigue. They are then ready once again to function.

During the period of adaptation, the usual photometric relationships are departed from. In other words, the apparent luminosity of an object may differ greatly from that to be expected from its actual illumination. A rather surprising example of this arises when two screens of the same material but greatly differing in their sizes are set side by side so that they are equally illuminated. The observer viewing them from some distance will find that the smaller screen appears distinctly less bright than the larger one. Another example of such an anomaly has already been mentioned above; this is the remarkable increase in the apparent brightness of an illuminated screen during the period of adaptation noticed by an observer who comes very close to it. Such an increase is not to be expected and is indeed not observed in ordinary circumstances.

Observations with monochromatic light: In the foregoing paragraphs, we have dealt with observations on the adaptation of vision to dim light, without concerning ourselves with the spectral characters, either of the bright light which determines the nature and duration of the process of adaptation or of the dim light which is sought to be perceived. It is evident, however, that these aspects require consideration, both in view of the theoretical interest of the subject, as also in view of its practical applications. In earlier chapters, studies on the luminous efficiency of the spectrum at different levels of illumination have been set out and it has been noticed that whereas at the highest levels, the yellow sector of the spectrum takes the leading position, this is no longer the case at the medium and lower levels. At these latter levels, the parts of the spectrum appearing both at the long-wave and the short-wave ends progressively diminish in importance. The red, orange and yellow sectors diminish in luminous efficiency and then fall out completely. Likewise, the regions which normally exhibit the colours of violet, indigo and blue lose their luminosity in the order stated and finally go out of the spectrum. At the lowest levels of illumination, therefore, we are only concerned with the green sector. The question then arises whether exposure of the eyes to

bright light appearing elsewhere than in the green sector of the spectrum would have any effect on the subsequent visibility of dim light. We have also to consider the relative efficiency of bright light in different parts of the spectrum in delaying the perception of faint light.

We shall first consider the influence of monochromatic light of high intensity on the visibility of dim light. Sources which are particularly suitable for such a study are a sodium-vapour lamp and a mercury-vapour lamp respectively, as they are commercially available with high candle-powers. The yellow light of a sodium-vapour lamp is sufficiently monochromatic and needs no filtration. Four plates of blue window-glass held together suffice to isolate the λ 4358 light of the mercury-vapour lamp from the other radiations accompanying it. A sheet of ground-glass held near the source is helpful as it diffuses the light which is viewed by the observer from a comfortable distance. The observations begin after allowing a sufficient period for complete dark-adaptation before the light of high intensity is switched on. It is switched off after an interval of say ten minutes. The observer thus turns towards a faintly illuminated screen which was clearly visible to him before the monochromatic light was switched on. The effect of exposure to this bright light on the visibility of the dimly lit screen then becomes apparent.

Observations with monochromatic yellow and blue light made in the manner described establish that these radiations have an effect of the same nature as that of exposure to bright daylight on the ability subsequently to perceive dim light. The process of adaptation to dim light shows the same sequence of phenomena in all these cases. Since the λ 5890 and λ 4358 radiations both lie outside the spectral range accessible to observation at the lowest levels of illumination, their ability to suppress or delay the perception of dim light is significant. It indicates that the effect of exposure to bright light on dim light vision is manifested even if the bright light does not lie within the wavelength range which is effective for perception at the lowest levels of illumination. This strongly supports the suggestion made above that the phenomenon of adaptation is to be interpreted as a recovery from a state of nervous fatigue produced by continued exposure to bright light.

Instead of monochromatic light, we may employ the white light emitted by a tungsten-filament lamp of high candle-power, viz., 1500 watts. A sheet of ground-glass which is one foot square and held at some distance from this source diffuses the light of the luminous filament. The observations are made in a completely darkened room by an observer whose vision has been fully dark-adapted in the first instance. He views the illuminated sheet of ground-glass through a pair of goggles which transmit only limited regions of the spectrum and accordingly exhibit the colours to be expected, viz., red, green or blue. The time of exposure to the bright light is the same in every case, viz., five or ten minutes. Immediately after the light is switched off, the observer removes the goggles and turns his eyes towards a dimly-illuminated white screen which was clearly visible to him in the first instance. It is found in every case that the screen is not visible at first, but later comes into view and progressively brightens up till it reaches its full original

brightness. This effect is most conspicuous, in other words, the time taken is longest, in the case of the green goggles. It is observed also with the red and the blue goggles, but is much less striking in their cases.

Localisation in the retina: A remarkable effect came under notice in the course of the studies set forth above. The illuminated sheet of ground-glass one foot square made use of in the studies and viewed steadily from a distance of two feet does not, of course, cover the whole field of vision of the eyes of the observer. When the bright light is switched off and the observer turns his eyes directly towards the dimly-lit screen, it falls within the field of view in the retina influenced by such exposure. It is not perceived in the first instance but later during the period of adaptation becomes visible with much reduced brightness. On the other hand, the dimly-illuminated screen as seen by averted vision is imaged on a part of the retina not previously exposed to bright light and it is visible immediately with its normal brightness. This difference in brightness of the screen as seen by averted and by direct vision however progressively diminishes during the period of adaptation and finally disappears. From these observations, it is evident that the effect of the incidence of bright light is limited to the regions of the retina exposed to it and that it does not extend over the rest of the retina. In other words, the effect is localised in the exposed regions.

The ability to perceive and locate the position of faintly luminous objects in a dark background is of great practical importance in certain circumstances, as for example, in the navigation of ships and in the operations of military aircraft. The maximum of sensitivity to dim light is then essential, and to secure this, the observer has to protect his vision from the effects of exposure to bright light. It may be remarked that these effects are particularly strong and of great duration if a source of light of high intrinsic intensity and of small angular extension is directly viewed for any appreciable interval of time. On the other hand, even brightly illuminated objects which are seen by the light which they diffuse and which cover extended areas in the field of vision produce effects which are, in comparison, negligible even after prolonged exposures. This is readily established by observational studies. The protection of the eyes from the effects of bright light by wearing coloured spectacles is a measure often adopted in practice. Since green light is found to produce the largest effects, filters which exclude this region of the spectrum but transmit the rest freely should be the most useful.

CHAPTER XIV

The chromatic responses of the retina

The technique for the observation of the living retina described in chapter III yields highly interesting and significant results, despite its extreme simplicity. As already set out in detail in that chapter, the observer seated at some little distance from a brilliantly lit white screen views it steadily for a few minutes through a selected colour-filter and then suddenly withdraws the filter, while continuing to view the screen with his attention fixed at some particular point on it. He then sees on the screen a picture which is a highly enlarged projection of his own retina, exhibiting colours dependent on the particular colour-filter which was employed. The picture is fugitive but can be restored and kept under view by the observer, merely by putting back the colour-filter before his eye and then suddenly removing it, again and again as often as desired.

Though colour-filters of gelatine on glass prepared with selected dye-stuffs are particularly well-suited for these studies, useful observations can also be made using such filters as are commonly available, e.g., plates or disks of coloured glass. We shall now briefly describe the effects observed in these cases. With a disk of yellow glass which cuts off the whole of the blue sector of the spectrum while freely transmitting all greater wavelengths, one finds on withdrawing the filter that the whole of the screen appears covered by a blue glow. The centre of the screen at which the observer has fixed his vision and where the projection of the fovea of his retina is located does not however exhibit this glow. It appears as a round disk with a sharply-defined edge and of a pale yellowish colour with a dark spot at the centre. The blue glow appears to be of uniform brightness over the whole of the screen under observation. When the observations are made with a filter of orange hue which cuts out wavelengths less than $540\text{ m}\mu$ while all greater wavelengths are transmitted, the effects observed are very similar to those noticed with the yellow filter, except that the glow of the screen is more brilliant and is bluish-white in colour and not blue. With a filter of red glass which transmits only wavelengths greater than $600\text{ m}\mu$ the observer notices on removing the filter that a round yellow spot appears on the screen where his vision had been directed. Elsewhere on the screen, a brilliant but short-lived glow is noticeable exhibiting a slightly bluish tint.

A beautiful effect is noticed when the observations are made with a plate of green glass which transmits light freely in the wavelength range between 500 and $570\text{ m}\mu$, but cuts out both longer and shorter wavelengths. When such a plate is

held before the eye for a minute or so and then removed, the region of the fovea appears on the screen as a disk of orange-yellow colour, while the rest of the screen exhibits a brilliant rose-red hue. The colour and the intensity of this hue as seen in the marginal parts of the screen and as seen in the area immediately surrounding the foveal spot differ very noticeably. The margins are of a deeper hue but less luminous than the region near the centre. When the observations are made with a plate of blue glass as the colour-filter, the foveal region appears as a disk of indefinite hue surrounded by a brighter field of a pale yellow colour. A bright spot can be seen at the centre of the fovea. Surrounding it a radial fibrous structure is visible bounded by a well-defined outer margin.

Filters of crystal violet: Quite spectacular effects are observed when gelatine films on glass dyed with *crystal violet* are employed for these studies. It is worthwhile making a set of five such filters dyed to various depths of colour, the lightest being a pale blue and the deepest a dark purplish-blue. Spectroscopic examination shows that the absorption by the dye exhibits two distinct bands, one which is fainter appearing in the green from 540 to 570 $m\mu$ and the other which is deeper in the orange-yellow from 590 to 620 $m\mu$. In the most heavily dyed filter, these bands spread out, their overlap resulting in a cut-off extending from 530 to 640 $m\mu$, while the rest of the spectrum is freely transmitted. With the most heavily dyed filter, the observer notices on its removal, a brilliant disk of green colour at the centre of the field with a bright spot at its centre and a radial structure surrounding the bright spot. Outside it, the observer also notices an extended area of circular shape of which the diameter is some five times greater than that of the foveal disk. The colour of this area is a greenish-yellow and its luminosity is much less than that of the central disk. Beyond this circular area and surrounding it is a region exhibiting an orange-yellow hue. With the less-heavily dyed filters, these effects become progressively less spectacular. In particular the luminosity of the central bright disk falls off rapidly, practically ceasing to be observable with the palest blue filter.

Cyanin filters: A set of six filters were prepared with this well known dye-stuff, their colours by transmitted light ranging from a deep blue to a light blue. The absorption spectra of the filters showed a regular progression, the deepest filter exhibiting a practically complete extinction of the yellow, orange and red regions in the spectrum, while the lightest filter showed a well-defined absorption band in the wavelength range from 630 to 670 $m\mu$. The visual effects produced and observed with these filters also alter in a progressive fashion. With the filter which exhibits a cut-off extending from the yellow towards greater wavelengths, the observer notices a disk of yellow light with a bright spot at the centre and a bright rim around its margin appearing in the foveal region. Surrounding this and exhibiting a yellow colour, a circular area also manifests itself which has a diameter some three times greater than that of the foveal disk. Outside this again,

there is a field of light extending to the outer limits of the screen and exhibiting an orange hue.

Observations with the other five filters show that the yellow foveal disk and the surrounding yellow region become less and less prominent in the series relatively to the outer parts of the field. With the two lightest filters, they can be observed only with some difficulty. On the other hand, the outermost areas continue to be visible and to exhibit colour. This colour shows a perceptible change from an orange to a reddish hue in the sequence.

Filters of cotton blue: This dye-stuff incorporates itself smoothly into gelatine films, making admirably clear filters exhibiting a blue colour of which the depth is determined by the quantity of the dye taken up. Spectroscopic examination shows that the absorption by the dye is strongest in the yellow region of the spectrum viz., at $580\text{ m}\mu$. The filters are completely transparent to the shorter wavelengths in the spectrum upto about $550\text{ m}\mu$. Beyond the yellow again, there is a sensible absorption which results in the orange and red of the spectrum being much weakened.

When such a filter is held before the eye of the observer who views a brightly-illuminated white screen for a little while and the filter is then removed with the vision fixed at a particular point on the screen, a picture of the observer's retina flashes into view. The most conspicuous feature in the picture is a bright yellow disk which is an enlarged image of the fovea with a bright yellow spot at its centre and a distinctly brighter rim around its margin. Encircling the foveal disk appears an area of circular shape with a fairly well-defined outer margin. This has a diameter some four times greater than that of the foveal disk. The colour of this region is yellow with a slight greenish tinge. The rest of the screen displays a glow of which the yellow hue is readily distinguishable from the colours noticed in the region which it surrounds.

Colour-filters of magenta: A set of three filters were prepared with this well known dye-stuff. All three showed a strong absorption in the wavelength range from 550 to $580\text{ m}\mu$, accompanied by a weaker and more diffuse absorption in the wavelength range between 500 and $550\text{ m}\mu$, while the rest of the spectrum showed no observable diminution of intensity in its passage through the filter. In effect, the most heavily-dyed filter cuts off the whole of the green in the spectrum, while the other two filters were less effective in this respect.

All the three filters behaved similarly when held by the observer before his eye and then quickly removed while he continues to view the illuminated screen with his attention fixed at a particular point in it. The only difference noticeable as between them is that the less strongly-dyed filters have to be held before the eye for a longer interval of time before being removed. Following the removal of the filter, the entire area of the screen exhibits a greenish-yellow glow which vanishes after a few seconds. But it may be instantly restored by putting back the filter and

then removing it again. In effect, the observer sees on the screen a projection of his own retina as illuminated by light in the wavelength range between 500 and 580 $m\mu$. This is made evident by the appearance at the centre of the field of a disk which does not exhibit the greenish-yellow glow seen over the rest of the screen and which is differentiated from the surrounding area by its relative feebleness and its pale blue colour.

From the foregoing, it emerges that the effects observed with the magenta filters are strikingly different from those exhibited by the other filters and described in the preceding paragraphs. These differences are clearly attributable to the regions of the spectrum exciting the response of the retina being different. It may be remarked that in the present case, we are concerned exclusively with the response of the retina to light appearing in the green sector of the spectrum.

The significance of the results: Numerous filters prepared with other dye-stuffs and exhibiting different depths of colour have been utilized for these studies. But it is unnecessary to describe the results obtained with them, since the examples dealt with in the foregoing paragraphs are sufficiently representative. The fact which impresses itself on the observer is that in nearly all cases, the picture of the fovea as seen on the screen differs notably both in its intensity and in its colour from the field which surrounds it. In some cases, as for example with the crystal violet filters, the fovea stands out brilliantly against a field of much lower intensity. In other cases, as for example, with the magenta filters, it is so feeble as to be discernible only with difficulty. These facts of observation may be summed up by the statement that the response of the foveal region to light appearing in the wavelength range from 560 to 600 $m\mu$ is far greater than its response to other parts of the spectrum and that it also differs notably from that of the retina elsewhere. It is worthy of note that the regions in the retina immediately surrounding the fovea also exhibit a behaviour which differs noticeably from that of the regions further away from it.

CHAPTER XV

The visual pigments

The results of the investigations described in the preceding chapters provide a firm basis for some inferences regarding the nature of the materials which enable the retina to function as a receptor of vision. It may be remarked that the spectrum of white light divides itself naturally into four sectors which may be referred to respectively as the blue sector, the green sector, the yellow sector and the red sector. The wavelength limits of the four sectors may be put respectively as from 400 to 500 $m\mu$, from 500 to 560 $m\mu$, from 560 to 600 $m\mu$ and from 600 to 700 $m\mu$. The subdivision of the spectrum into four parts with the wavelength limits assigned to them is based on the observed behaviour of the spectrum in the respective ranges. The red sector of the spectrum is the first to disappear from sight when the level of illumination is lowered sufficiently. Likewise, the blue sector is that which goes out of sight last, leaving the green sector as the one which continues to be visible at very low levels of illumination. The yellow sector is the most luminous of all the sectors at high levels of brightness, but it progressively becomes weaker at lower levels and when the red sector has gone out of sight, it also follows suit.

The blue sector: Evidence from diverse sources enables us definitely to identify the visual pigment which functions in the blue sector of the spectrum as a carotenoid. The carotenoids are pigments of vegetable origin which find their way into human blood through the food products which are consumed. The two pigments of this nature with which we are here concerned are β -carotene of which the chemical formula is $C_{40}H_{56}$ and xanthophyll of which the composition is indicated by the formula $C_{40}H_{56}O_2$. Both of these pigments have elongated molecules terminating in end-groups, each of which contains a closed ring. The chemical relationship between the two compounds is indicated by the fact that xanthophyll is also known as a dihydroxy- α -carotene, the two hydroxyl groups occupying positions in the end-rings which terminate the molecule. The light absorption curves of the two compounds are not quite the same. The curve for a solution of xanthophyll in hexane is reproduced below. It will be seen that the strength of the absorption drops steeply down from a maximum at 475 $m\mu$ to a low value at 500 $m\mu$ and becomes quite small at still greater wavelengths. At 445 $m\mu$, there is another peak of strong absorption, and still another peak at 420 $m\mu$, while intermediately, there are dips in absorption located at 460 and

430 $m\mu$ respectively. The absorption strength falls off rapidly as we proceed from the peak at 420 $m\mu$ further towards the ultra-violet.

There is a close correspondence between the features exhibited by the light-absorption curve of xanthophyll and the observed characters of the blue sector in the spectrum of white light. The limits of the blue sector have been indicated as the wavelengths between 400 and 500 $m\mu$. It will be seen from figure 7 that this is also

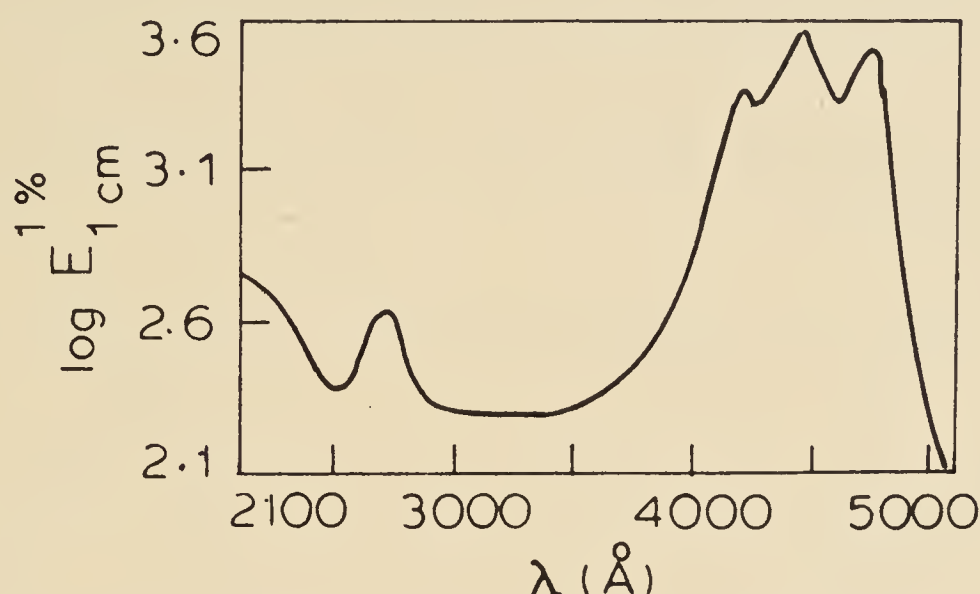


Figure 7. Light absorption curve of xanthophyll in hexane solution (after Karrer and Jucker).

the range in which the absorption of xanthophyll is most marked. A noteworthy feature in the spectrum of white light is the very rapid change in colour from blue to green manifesting itself at 490 $m\mu$, a traverse of 10 Å in wavelength along the spectrum being sufficient for a readily observable difference in colour. This is precisely the location in the spectrum where the curve of light-absorption for xanthophyll drops steeply from a high to a low value. We are therefore justified in regarding the rapid colour change as a consequence of the pigment functioning in the blue becoming less effective and giving place to another pigment functioning in the green.

A further remarkable parallelism is the appearance of bands of higher luminosity in the spectrum which coincide in their respective positions with the absorption maxima of xanthophyll. The observer views the first-order diffraction spectrum of a luminous tungsten filament produced by a grating held before his eye. The bands commence with a noticeable fall in luminosity in the spectrum where the green ends and the blue begins. Following this, a bright band with a maximum of intensity at 470 $m\mu$ is readily recognisable. A further drop in luminosity is followed by a recovery and a second maximum of brightness at 435 $m\mu$ is noticed. Beyond this again, there is a further drop in intensity followed by a recovery in which the third and last maximum at 410 $m\mu$ is discernible. The first maximum at 470 $m\mu$ falls in the blue region, the second maximum at 435 $m\mu$ in the indigo and the third maximum at 410 $m\mu$ appears in the violet.

It may be remarked that these features observed in the spectrum of white light lead us to identify the visual pigment functioning in the blue sector as xanthophyll and not as β -carotene. The reason for this will be evident when we compare figure 7 which is the light-absorption curve of xanthophyll with figure 8 which is the curve for β -carotene dissolved in hexane. There are some noteworthy differences between the two absorption curves. The absorption by β -carotene extends well beyond 5000 Å into the green and its steepest fall appears at 5000 Å, instead of 4900 Å as in the case of xanthophyll. The third maximum in the case of β -carotene is a relatively inconspicuous dip in a steeply falling part of the curve unlike the well-marked feature noticed with xanthophyll. These features disqualify β -carotene for recognition as the visual pigment functioning in the blue sector of the spectrum.

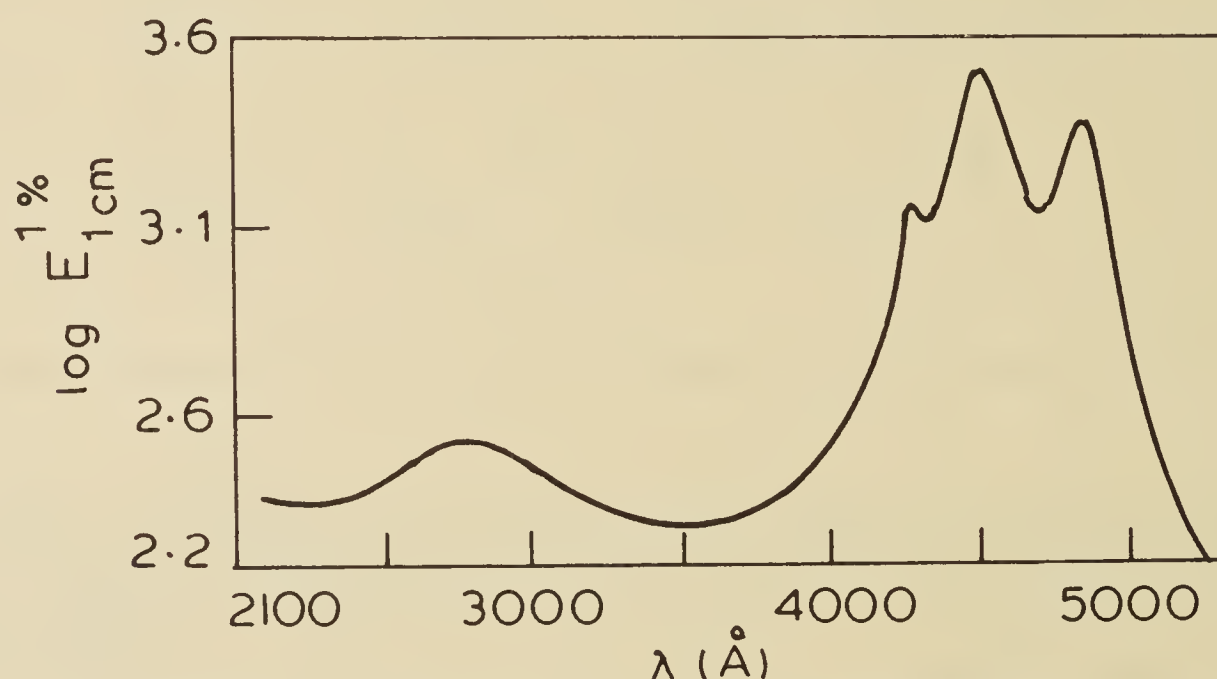


Figure 8. Light absorption curve of β -carotene in hexane solution (after Karrer and Jucker).

It is scarcely surprising that it is xanthophyll and not β -carotene that plays the role of visual pigment. For, as is well known, xanthophyll is not a precursor of vitamin-A, whereas β -carotene possesses high vitamin-A potency and is known to break up into two equal fragments to form vitamin-A and that this again is a constituent part, along with proteins, of the substance long-known and recognised as the "visual purple" present in the retina. This visual purple is a photo-labile substance, evidently intended as a protective material to prevent damage by light to the delicate tissues in the retina and to maintain them in a healthy state. But the same photo-labile nature disqualifies it from functioning as a visual pigment properly so-called, for which we need a material that is chemically stable and which can pass on the light-energy which it absorbs without itself suffering destruction.

The conclusions arrived at in chapter IX regarding the perception of polarised light by our eyes may here be briefly recalled. Viewing a brilliantly

illuminated surface through a polaroid sheet and a colour-filter which transmits only the blue light of the spectrum, we observe two brushes of light in the field crossing each other, one which is perfectly dark and the other is a bright blue and these brushes rotate in the field when the polaroid is rotated. From the detailed study of this phenomenon, it emerged that it owes its origin to the radial structure of the foveal region in the retina and to the material which enables us to perceive blue light having elongated molecules which orientate themselves along the radii of this structure. This finding is in agreement with the identification of the visual pigment for the blue sector of the spectrum as xanthophyll.

Some general remarks: The carotenoid pigments owe their power to absorb light in the visible region of the spectrum to the presence in their molecular structure of a succession of conjugated ethylenic bonds, e.g., eleven such bonds in β -carotene and ten such in xanthophyll. That a yellow pigment is present in the retina is indicated by ophthalmoscopic observations through colour-filters. That this pigment is xanthophyll and that it is the vector of vision in the blue part of the spectrum is established by the facts set forth in the preceding paragraphs. The blue of the spectrum, though colourful, is of low intensity, the visual luminosity at $450\text{ m}\mu$ being less than a twentieth part of that observed in the yellow at $580\text{ m}\mu$ at the ordinary or daylight level of illumination. This indicates that the carotenoids are of low efficiency as visual pigments and suggests that the visual pigments which function in the more luminous parts of the spectrum are of a different nature. That they are products of human metabolism may be taken for granted. For, it can scarcely be supposed that the functioning of the visual organs which is so fundamental to life would be left solely to depend on materials which adventitiously find their way into the blood stream.

A group of organic compounds exhibiting colour and playing highly important biological roles are known as the pyrrole pigments. Amongst them may be mentioned particularly the chlorophyll present in the green leaves of plants and the colouring matter of red blood. Most pyrrole pigments contain four pyrrole rings linked by four carbon atoms which hold them together in the form of a closed planar ring containing a large number of conjugated double bonds. The porphyrins are compounds of this nature and when dissolved in organic solvents exhibit a typical four-banded absorption spectrum in the visible region. An atom of the metallic element iron can replace the two atoms of hydrogen within the tetrapyrrolic ring, the iron atom being then equally bound to the four nitrogen atoms. Compounds of this nature are known as hematins. These are found widely distributed in the cells of plants, animals and micro-organisms. As examples, may be mentioned the cytochromes which exhibit characteristic absorption spectra in the visible region.

Various considerations suggest that the visual pigments which function in the red, yellow and green sectors of the spectrum and enable us to perceive light in these parts of the spectrum are *heme* pigments, in other words, iron-porphyrin

complexes linked to protein. They are compounds of which the absorptive power for light is great and there is good reason to believe that they can function efficiently as visual pigments. No special assumptions are necessary to account for their presence in the retina. For, the bacillary layer which contains the retinal structures functioning as visual receptors is directly in contact with the choreocapillary layer and the choroidal membrane which are highly vascular and are in a position to supply these materials. A further important remark is that a *heme*-protein complex can appear in three different forms or states, viz., the ferrous, the oxygenated ferrous and the ferric states, the absorptions by which lie in different parts of the spectrum. The entire visible spectrum other than the blue can thus be covered by these pigments.

The yellow sector of the spectrum: The absorption of light by the *heme* pigments *in vivo* is readily demonstrated with the aid of a pocket spectroscope. If, through the instrument one views the averted eye-lids or the lips of any person, it will be noticed that an intense dark band obscures the yellow sector in the spectrum and covers the spectral range between 570 and 590 $m\mu$. A fainter band can also be seen in the green region of the spectrum in the vicinity of 540 $m\mu$. The intense absorption in the yellow sector which thus comes into evidence is a characteristic property of the oxygenated form of the *heme* pigments. The presence of material of this nature in the retina would explain not only our ability to perceive yellow light but also various characteristic features of the yellow sector of the spectrum studied and described in earlier chapters. The intensity of the absorption centred at 580 $m\mu$ would result in the yellow of the spectrum, in appropriate circumstances exhibiting a high degree of luminosity, indeed higher than any other part of the spectrum. The spectral sharpness of the absorption would also result in a highly developed power of colour discrimination in that part of the spectrum. This has already been demonstrated by the measurements made by two different methods and fully set out in Chapter VIII. At the wavelength of 5800 Å, a traverse of 15 Å along the spectrum in either direction is sufficient to give rise to an observable change of colour. Thus, the identification of the visual pigment for the yellow sector finds itself confirmed in three different ways: *firstly*, the precise agreement in the position of its spectral absorption with the location of the yellow sector; *secondly*, the strength of the absorption which is capable of explaining the observed great luminosity of the yellow sector and *thirdly*, the high power of colour discrimination in this region which is to be expected by reason of the sharpness of the absorption band.

The red and the green sectors: The recognition that the *heme* pigment in the oxygenated ferrous state enables us to perceive the yellow in the spectrum leads us to assume that the same pigment in the reduced ferrous state and in the ferric state can similarly function respectively in the green and the red sectors of the spectrum. Definite evidence that this is actually the case is forthcoming when we

set the spectroscopic behaviour of the pigments of this nature as determined by laboratory studies alongside of the observed features of human vision.

One of the most striking characteristics of human vision is that the extension of the red end of the spectrum depends greatly on the strength of the illumination. At fairly high levels of illumination, the spectrum may extend upto $700\text{ m}\mu$ or even beyond. But as the level of brightness is lowered, the spectrum contracts in a readily observable fashion, the limit of visibility falling to $650\text{ m}\mu$ very quickly, and then more slowly to $630\text{ m}\mu$. It remains at $630\text{ m}\mu$ until a further large drop of luminosity leads to the complete disappearance of the red from the spectrum. From these facts of observation, it may be inferred that the visual pigment functioning in the red sector presents a definite maximum of absorption at the wavelength of $630\text{ m}\mu$ and that at greater wavelengths, the absorption drops down steeply to very low values. This is the actually observed spectroscopic behaviour of the *heme* pigment in the ferric state.

A further striking confirmation of this identification is forthcoming from the studies of the power of colour discrimination in the spectrum described in Chapter VIII. It was there shown that results of the measurements indicate a feature analogous to that observed at $580\text{ m}\mu$ in the yellow but of a less striking nature in the red at $630\text{ m}\mu$. From the shape of the graph at this wavelength, it may be inferred that a maximum of the absorbing power of the visual pigment is there located.

Laboratory studies of the spectroscopic behaviour of the *heme* pigment in the fully reduced ferrous condition show that it exhibits a powerful absorption in the spectral range between 580 and $520\text{ m}\mu$ with a maximum at $555\text{ m}\mu$. The molecular coefficient of extinction of the ferrous form of the pigment at $555\text{ m}\mu$ is about four times greater than for the absorption at $630\text{ m}\mu$ of the ferric form of the pigment. This great difference helps us to understand why the green sector of the spectrum is much more luminous than the red sector and survives at the low levels of illumination at which the red sector has completely disappeared.

A further remark may be made, viz., that in the wavelength range between 500 and $600\text{ m}\mu$, the effects of all the three forms of the *heme* pigments would be superposed. The observed results would be determined by their relative proportions as well as by their effectiveness at each wavelength in the range under consideration. Why we observe a continuous sequence of colour in the spectrum and not just three sharply divided colour sectors is thereby made intelligible.

CHAPTER XVI

Defective colour vision

It is appropriate that normal and abnormal colour vision are dealt with in chapters which follow one after the other. Being related subjects, the methods adopted for their study are necessarily the same or similar, and the findings have to be considered together in any final assessment.

Earlier in this work, we had to discard the idea that the perception of the colour of yellow light in the spectrum is a secondary or derivative sensation resulting from the superposition of the red and green sensations as primaries. The recognition of spectral yellow as an independent sensation is indeed necessary in any rational approach to the subject of colour. In the preceding chapter, we have seen that the visual pigment which functions in the yellow is different from those functioning in the red and green sectors of the spectrum, though standing in a close chemical relationship to them. Likewise, it is not possible to arrive at any understanding of the nature or origin of defective colour vision unless it is recognised at the outset that the sensation of yellow stands in a category by itself independent of either red or green. Indeed, this becomes clear when Dalton's own statement regarding his personal colour perceptions is recalled. He is quoted as having said that he could only distinguish in the spectrum two hues, viz., yellow and blue, the former being perceived over the entire range of the spectrum in which normal observers perceived the usual succession of red, orange, yellow and green, while he perceived as blue the region which others perceived as blue and violet, though he also recognised the violet appearing as a more saturated blue.

Dalton's description of the spectrum of white light is closely matched by that given by an observer who will be referred to here by the pseudonym of Asoka and who being a qualified man of science could be trusted to describe accurately what he himself saw. Asoka was presented with the spectrum of a very brilliant source of white light appearing on the ground glass screen of a constant-deviation spectrograph, arrangements being made to vary the brightness of the spectrum over a wide range of values. He placed the commencement of a spectrum of moderate or high luminosity at the long-wave end precisely where it is placed by a normal observer. But he described the parts of the spectrum where a normal observer sees red, orange, yellow and green as being yellow in colour. He also placed the point of maximum luminosity in the spectrum at the same position as an observer with normal vision, viz., at $580\text{ m}\mu$. Asoka observed the luminosity to fall off in the region of transition where the colour changes to blue, as is also

noticed by a normal observer. The blue of the spectrum was named by him as blue and its termination as placed by him agreed with that noticed by normal observers. The spectrum at a low level of luminosity did not appear to Asoka to exhibit colour, though to a normal observer, the green was clear enough. The long-wave end of the spectrum had shifted to shorter wavelengths, alike to Asoka and to an observer with normal vision. The point of maximum luminosity in the spectrum had also shifted towards shorter wavelengths and to the same extent for Asoka as to a normal observer.

More detailed studies were made by other observers who were also qualified scientific men. We shall here reproduce *verbatim*, what a physicist who will be referred to here as Krishna wrote when he was asked to view the bright sky through a Zeiss pocket spectroscope provided with a wavelength scale in the eye-piece and to record what he saw. "The spectrum appears visible at about 4100 Å where it is violet, and the blue is distinct at 4300 Å and extends to 4750 Å where the transition to green begins. The green is visible from 4750 to 5000 Å. The region 5000 to 5200 Å is greenish-yellow. The yellow which is what appears as the brightest part of the spectrum extends from 5200 to 6000 Å. This is followed by the orange from 6000 to 6200 Å, while the red region is covered by 6200 to 6750 Å. My estimate of the region of maximum luminosity would be at 5700 to 5800 Å."

It will be seen that while Krishna puts the orange and the red where a normal observer would perceive those colours, his yellow extends towards shorter wavelengths and covers the region described by a normal observer as green. It is therefore not surprising that the green and the yellow lines of a mercury-lamp as seen through the spectroscope did not appear to Krishna to be of different colours.

Of particular interest are the observations recorded by a young science student who will be here referred to as Dhruva who was asked to record the colour of the spectrum of a brilliant source of white light, emerging through a slit placed within the eye-piece of a wavelength spectrometer.

Dhruva recorded the colour seen by him from 720 to 680 mμ as red, from 680 to 670 mμ as orange, from 660 to 530 mμ as yellow, from 520 to 510 mμ as green, from 500 to 470 mμ as blue and from 460 to 440 mμ as violet. The enormous range of the spectrum perceived by Dhruva as yellow in colour is noteworthy. A large part of the region described by a normal observer as red was perceived by Dhruva either as orange or as yellow. A large part of the spectrum perceived by a normal observer as green was also perceived by Dhruva as yellow. It is evident that his vision is a closer approximation to the Daltonian type than that of Krishna.

Mention may also be made of the reports made by three other observers. The physicist whom we shall refer to here as Arjuna was aware of the deficiency in his own colour perception, having noticed that the green and the yellow lines of a mercury-lamp as seen through a spectroscope did not appear to him to differ in colour. He described the spectrum of white light as consisting of red and orange regions followed by a bright yellow, light blue, dark blue and violet. At very low

levels of illumination, only the region that had appeared yellow continued to be seen, but it then exhibited no colour except at the long-wave end where it appeared as slightly orange.

Another physicist who will be referred to here as Ganesh was asked to map the colours of the spectrum with the aid of a wavelength spectrometer. Commencing at the violet end, he listed the wavelengths at which the colours mentioned made an appearance as follows: violet, 415 m μ ; indigo, 421 m μ ; blue, 440 m μ ; blue-green, 470 m μ ; green, 495 m μ ; yellow 523 m μ ; orange, 620 m μ ; red, from 680 m μ upto the limit 750 m μ . It will be noticed that in the colour perceptions of Ganesh, the sensation of yellow appears over the part of the spectrum seen by normal observers as green, yellow and orange, while a large part of the spectrum which appears red to normal observers is perceived by Ganesh as orange in hue.

A science student whom we shall name here as Drona was aware of his defective colour vision since he could not perceive the difference between the green and the yellow lines in the spectrum of the mercury vapour lamp. Viewing the spectrum of a tungsten-filament lamp through a wavelength spectrometer, he reported the following sequence of colours and their respective wavelength ranges, red from 710 to 630 m μ ; orange from 620 to 610 m μ ; yellow from 600 to 540 m μ ; light green from 530 to 510 m μ ; green 500 m μ ; bluish-green 495 m μ ; blue 490 to 475 m μ ; intense blue from 470 to 450 m μ . It is clear from these figures that Drona's colour sensations differ considerably from those recorded by Dhruva and by Ganesh.

The nature of defective colour vision: To an observer with normal vision, the spectrum of white light exhibits two regions in which the progression of colour is exceptionally rapid. One of them is at 490 m μ where the perceived colour changes from blue to green. The other is at 580 m μ which is the centre of the yellow sector. Here the alteration of colour with wavelength is so rapid that the two lines of the yellow doublet 5770–5790 Å in the mercury spectrum are observably different in hue. In the wavelength range from 580 to 630 m μ , the colour to a normal observer alters rapidly from yellow through orange to red. Beyond 630 m μ , the luminosity falls off and the colour-progression slows down.

From the reports of the observers named above, it is clear that the colour-change in the vicinity of 490 m μ is perceived by all of them. But the progression of colour at 580 m μ has disappeared. To all of them, the yellow doublet and the green line of the mercury spectrum appear indistinguishable in colour and the part of the spectrum seen as yellow has extended itself so as to cover the whole or nearly the whole of the range of wavelengths perceived by a normal observer as green in colour. An extension of the yellow region towards greater wavelengths is also evident from the reports of three of the observers, viz., Asoka, Dhruva and Ganesh, what is normally perceived as orange or red being perceived by them as yellow or as orange. But the reports of the other three observers, Krishna, Arjuna and Drona do not indicate such an extension.

The recognition that the yellow of the spectrum is an independent sensation which is distinct in its origins from either the red or the green leads us to a simple and quite natural explanation of the differences between normal and defective colour vision. In the spectrum of white light as seen by an observer with normal vision, there is a considerable overlap of the regions in which green, yellow and red are respectively perceived. That indeed is the reason why the green of the spectrum passes over to the yellow in a continuous fashion, a greenish-yellow being a recognisable stage. Likewise, the progressive change from yellow to red is evident in our perception of orange as a colour different from either. Defective colour vision is then readily explicable as the result of a large increase in the strength of the yellow sensation relatively to the green and the red sensations. The regions of the spectrum in which there is an overlap between yellow and green or between yellow and red would then exhibit altered colours different from those seen by a normal observer.

The green and the yellow of the spectrum of white light appear in closely adjacent regions. The maximum of the green sensation is at about $555\text{ m}\mu$ and the maximum of the yellow is at $580\text{ m}\mu$. That there is a large overlap of the green and yellow sensations is clear from the fact that a progressive change of colour between 520 and $560\text{ m}\mu$ is noticeable to an observer with normal vision. It is therefore to be expected that a large increase in the strength of the yellow sensation relatively to the green sensation would, in the region of overlap, make it impossible to distinguish colours which to a normal observer appear as green and yellow respectively.

The position is not quite the same with regard to the perception of colours in the red region of the spectrum. The maximum of the yellow at $580\text{ m}\mu$ and the maximum of the red at $630\text{ m}\mu$ are well separated from each other. The red of the spectrum also extends, though with reduced intensity upto $700\text{ m}\mu$ and even beyond. The region of overlap between the yellow and the red which appears orange to a normal observer is in the wavelength range from 600 to $620\text{ m}\mu$. Any large increase in the strength of the yellow sensation would result in the orange being perceived as yellow, and it might also result in the sensation of orange extending further into the red. But the replacement of the red sensation by the perception of yellow over the entire spectrum must be regarded as rather an exceptional case.

It is worthy of remark that there is a fairly close resemblance between the appearance of the spectrum of white light to an observer with defective colour vision and its appearance to an observer with normal vision at very high intensities of illumination. For this purpose, an extremely brilliant source of white light, e.g., a tungsten-filament of the kind used in projection lanterns, may be viewed through a replica grating held in front of the eye. In the first-order spectrum of this source as seen from a great distance, it is possible to distinguish the separate regions in which the blue, green, yellow, orange and red appear. But when the observer moves closer to the source and the spectrum then shortens and

becomes much more brilliant, the green, yellow and orange merge into a single band of colour in which the differences between them are barely recognisable.

Likewise, one may expect that the appearance of the spectrum of white light to an observer with defective colour vision would alter at low levels of illumination in such manner as to approach more closely to what is seen by a normal observer. This is found to be actually the case and the explanation given above of the origin of defective colour vision thereby finds impressive support. For this purpose, the spectrum of the light emitted by a long luminous tungsten-filament at various temperatures is viewed through a replica diffraction grating. Two of the observers, viz., Krishna and Arjuna named earlier, were asked independently to make such observations and record by sketches what they saw. Their observations as subsequently compared were substantially in agreement. At low levels of brightness, viz., when the filament emitted a dim red glow, its spectrum presented much the same appearance to them as to an observer with normal colour vision. But as the spectrum brightened up, the yellow sector made an appearance and then spread out, progressively replacing the green sector and to some extent also the red sector, till a high levels of brightness the extent of its spread far exceeded the width of the regions exhibiting other colours on either side of it.

Colours of interference patterns: The colour vision of the observers named above was also examined by other methods besides those set forth in the preceding paragraphs. A particularly interesting and significant technique of ascertaining their perceptions of light and colour was to present interference patterns on a large scale as seen by white light and ask them to record a detailed description of what they saw in the patterns. Not having been subjected to such a test earlier, the observer's statement would be entirely unprejudiced and hence would be of special value. Further, the comparison of their descriptions with the results of the studies of these same patterns made by an observer with normal vision and set forth in Chapter VII above could be expected to be particularly illuminating.

The first of such tests was made with the observer named above as Asoka. He was shown the coloured rings of an interference pattern formed on a large scale and had no difficulty in counting the number of rings visible in it, which he gave as seven. But the rings appeared to him to be yellow in colour and to be separated from each other by darker circles. In the first two or three of these rings he noticed that indications of blue were visible.

Both the circular ring pattern and the straight fringes due to a wedge-shaped air film were studied by the other observers and the features noticed by them were recorded in detail. An intercomparison of the descriptions given by them and of the features in such patterns as seen by a normal observer discloses both the points of agreement and the points of difference to be expected. It will suffice here to mention the descriptions given by Dhruva of the Newtonian ring pattern, as it is typical of the manner in which such a pattern presents itself to an observer

whose colour vision approximates to the Daltonian type. Around the central dark spot, there is a broad region exhibiting a light blue colour with an outer yellow fringe. These are surrounded by a dark blue circle which is the most prominent feature in the entire pattern. This is followed by a wide ring of yellow colour which is very prominent by reason of its luminosity. Following this again is a circle with a very distinct blue colour of which the width is slightly less than that of the one previously mentioned. The next ring again is a yellow circle not so distinct as that mentioned earlier. The next ring again is a blue circle of very light colour. Further out, there are other rings in which alternations of colour may be perceived, but they are not distinct and cannot be accurately described.

CHAPTER XVII

The visual synthesis of colour

Colours of varied nature present themselves to us in diverse circumstances. Of particular interest are those cases in which the colour has a physical origin and manifests itself as natural phenomena on a large scale, viz., the blue of the sky, the colours of sunrise and sunset, and the dark blue of oceanic waters. In the biological field, familiar examples are the colours of birds and butterflies and of the foliage and flowers of trees and plants. Man-made products such as textiles and ceramics utilize colour to enhance their attractiveness. The list of artificial products displaying colour includes a variety of dyes, pigments and paints. All such cases have, as a common feature, the fact that the observed colour arises from a superposition of light from different parts of the spectrum reaching the eyes of the observer simultaneously. The observed colour is accordingly in the nature of a composite sensation, as distinguished from the pure colours of the spectrum.

The problem thus presents itself of determining the nature of the relationship between the perceived colour and the spectral characteristics of the light that produces the sensation. The obvious procedures for dealing with this problem are empirical methods which may be divided into two groups, viz., the analytical and the synthetic. The analytical procedure employs the spectroscope to determine the characteristics of the light perceived by the observer and by noting their relationship to the colour in numerous cases seeks to arrive at certain general conclusions. The synthetic procedure makes use of various devices by which selected colours are superposed on each other, and the results of such superposition are observed. The defects of this latter method are obvious. For, the selection of the colours chosen for the superposition is necessarily arbitrary and the conclusions drawn from such observations are therefore of questionable validity.

Already in an earlier chapter which dealt with the colours exhibited by interference patterns, it has been shown that the study of such patterns yields results which are highly significant for our knowledge of the characteristics of human vision. In a later chapter, it will be shown that the study of the colours of rotatory dispersion likewise yields further results of importance. The special advantage of using such physical methods is that they enable us to study the colours of light of which the spectral composition is precisely known and can be varied at will to cover a diversity of cases. The validity of the conclusions thus arrived at is thereby ensured.

But empirical methods, however useful they might be, cannot enable us to reach a complete understanding of the subject. For that purpose, it is necessary to proceed from first principles and endeavour to ascertain how the visual perceptions of composite light are determined by the physical nature of light and the processes by which the sensations of light from different parts of the spectrum are summed up by the visual mechanism. In following this road to knowledge, we have of necessity to make use of the results obtained and set forth in our earlier chapters regarding the perception of the colours of monochromatic light.

Various considerations indicate that the two parts of the spectrum of which the wavelengths are respectively smaller and greater than 5000 \AA should be regarded as distinct units in relation to the present subject. The junction between the two parts is a region in the spectrum at which a rapid change of hue is a noteworthy feature. Colour-filters are available which freely transmit one part of the spectrum as thus divided up and cut off the other, or *vice versa*. The colour of the filters having this property as seen by transmitted light is a bright yellow in one case, and a bright blue in the other. The filters are complementary, so that if they are held together, no light passes through the combination. If a white card illuminated by direct sunlight is viewed through the yellow filter, it appears dazzlingly brilliant. But as seen through the blue filter, the card appears bright but by no means exceptionally bright. It thus becomes obvious that there is an enormous difference in the integrated luminosities of the two parts of the spectrum. Nevertheless when they are superposed, the colours are suppressed and we perceive only white light. This, indeed, is one of the most remarkable features of human vision.

In numerous cases, colour results from the selective absorption of particular regions in the spectrum, while the other regions are freely transmitted and appear in the light transmitted through the material. Using substances with these properties which are freely soluble in water and by varying the concentration of a solution of the substance contained in a cell of moderate thickness, an observer can follow the changes in the colour and intensity of the transmitted light and determine how these changes are related to the characters of the spectrum of the transmitted light which is also kept under view. By this simple technique, it is possible to study numerous examples and arrive at some useful results. We shall here refer to some particular cases from which significant conclusions emerge.

Cuprammonium: Dissolving copper sulphate in distilled water and adding ammonia in excess, we obtain a solution exhibiting a characteristic blue colour. When the concentration of the solution is high, the transmission by it is confined to the region of the shortest wavelengths and indeed, the cuprammonium filter is usually employed for isolating this part of the spectrum. When, however, the solution contained in a cell 2 cm thick is progressively diluted by addition of distilled water, striking changes may be observed in the spectrum of the light transmitted by it. The transmission, which at first is confined to the violet end of

the spectrum, extends towards longer wavelengths. It ceases to be confined to the blue region of the spectrum and the green sector is also transmitted. This progressively gains in strength until as seen through the spectroscope, the green actually appears more luminous than the blue sector. With further dilution, the transmission extends into the orange and the red of the spectrum, but the yellow region remains faint, the orange and the red much exceeding it in brightness. Throughout this series of changes, the colour of the transmitted light is perceived as blue. The observations make it evident that the blue colour of the transmitted light and the extinction of the yellow in its spectrum are connected phenomena.

Even when the cuprammonium solution is extremely dilute, the colour of the transmitted light remains blue. The blue sector of the spectrum is present in full strength, while the green sector shows no appreciable weakening. But the strength of the yellow sector is much weakened. The red sector is still quite strong, but the reduction of its intensity is noticeable and a slight contraction is also remarked at the end of the spectrum. The situation may be summed up by the statement that as the result of the changes noted above, all other colours in the spectrum are suppressed or masked from observation by the blue which alone is the perceived colour.

Chromium chloride: Strong solutions of the chloride of chromium exhibit a deep green colour which owes its origin to a transmission band in the 500 to 550 m μ region of the spectrum. Holding up a cell containing such a solution against a strong light and examining the light coming through it with a pocket spectroscope, the transmission band in the green is found to be accompanied by another located near the red end of the spectrum. It is the intermediate region containing the yellow of the spectrum which is most strongly absorbed. Dilution by successive additions of distilled water results in a large increase in the brightness of light transmitted by the cell, but the colour remains green. Spectroscopic examination in these circumstances reveals that the band of transmission in the green has broadened in either direction and that the red sector has also made its appearance in the transmitted light. When the dilution has been carried far enough, the red region of the spectrum is quite conspicuous and it is only a little less bright than it is normally. But the yellow sector is much weakened.

It is noteworthy that the colour of dilute solutions of chromium chloride remains green, despite the presence of the red sector with considerable strength and the feeble extension into the blue that is also noticeable. It is to be inferred that as a result of the weakening or extinction of the yellow in the spectrum, the green which is present in full strength succeeds in suppressing or masking from observation all the other colours.

The purple sensation: The dye-stuff bromcresol purple when dissolved in water and highly diluted exhibits a dark band of absorption covering the wavelength

range from 570 to 610 $m\mu$, there being no noticeable absorption of either shorter or longer wavelengths. In other words, the red, green and blue sectors of the spectrum are freely transmitted and only the yellow sector of the spectrum is extinguished. The colour of the transmitted light is purple and this is evident even with extremely dilute solutions.

Very dilute solutions of the dye-stuff bromphenol blue exhibit a powerful absorption in the wavelength range from 575 to 610 $m\mu$, while freely transmitting the rest of the spectrum. A cell containing the solution exhibits a purple colour. Stronger solutions exhibit an absorption covering the spectral range from 540 to 620 $m\mu$, and transmit light of a deeper purple colour.

Crystal violet and methyl violet are two other well known dye-stuffs which exhibit a powerful absorption of the yellow sector of the spectrum besides a relatively weak absorption appearing in the green sector. Very dilute solutions of both of these dyes exhibit a purple colour by transmitted light.

Solutions of rhodamine: Spectroscopic examination of the light transmitted through a cell containing this dye-stuff at various stages of dilution and observations of the corresponding changes in the colour of the light which comes through are highly instructive. Weak solutions show an intense absorption covering the wavelength range from 530 to 570 $m\mu$. Increasing the concentration step by step, a stage is reached at which the green sector of the spectrum from 500 to 570 $m\mu$ is totally extinguished without any noticeable reduction in brightness of the rest of the spectrum. At this stage, the colour of the transmitted light is a rich rose-red, which we therefore recognise as the true complementary colour to the green. Weaker solutions give a similar colour but of less saturated hue.

When the strength of the solution is further increased, the absorption band extends towards smaller wavelengths, and by successive stages reduces the extension of the blue sector. The colour of the transmitted light then changes progressively from rose-red to a fuller red. The blue of the spectrum, though visible in the spectroscope, is masked or suppressed from observation by the red sector which is present in full strength.

We may sum up the results which emerge from the foregoing studies. As will be seen in later chapters of the book, they are in full agreement with what is observed in numerous other cases. The highly important role in vision played by the yellow sector of the spectrum has already been remarked upon in earlier chapters. It now emerges that this region of the spectrum practically controls our perceptions of the colours of composite light, its presence or absence making all the difference to the sensory impression which is produced. A particularly interesting case is that in which the yellow sector is absent, while the red, green and blue sectors are present in their normal strength. The composite sensation is then the well-known and easily recognised purple colour.

Another important finding is the colour which is complementary to the green of the spectrum, in other words, the composite sensation which results from a

superposition of the red, yellow and blue sectors in the spectrum of white light. This is both accurately and suitably described as rose-red, for the reason that the petals of many varieties of roses exhibit the colour, the origin of which is an absorption of the green sector of the spectrum by their petals; the more complete is such absorption, the deeper is the colour observed.

The masking of colours from perception by other colours which are present in strength is another phenomenon of great interest which comes into evidence in the cases dealt with in the foregoing paragraphs. We shall meet with numerous other cases of the kind in later chapters. The visual processes which result in such masking will also be considered in due course.

CHAPTER XVIII

The superposition of spectral colours

Light which is not monochromatic but appears simultaneously in different parts of the spectrum is perceived by our eyes. What is the nature of the visual process which sums up the effects of the different spectral components and what is the final result? These issues are obviously of a fundamental nature and they will be dealt with in the present chapter. We shall in the first place indicate the theoretical approach made to the subject and deduce certain observable consequences. We shall then proceed to describe the techniques of study which enable these consequences to be tested experimentally. The results are found completely to confirm the theoretical expectations.

The perceptions of light and colour are the result of certain processes in which the retinae of our eyes play the leading role. The picture of these processes which has emerged from the studies described in the preceding chapters of this book is that we are concerned with certain pigmentary substances present in the retina which absorb the energy of the incident light and thereby enable it to be perceived. Four such substances have been recognised. One of them is a carotenoid pigment which functions in the wavelength range extending from the extreme violet end of the spectrum upto the boundary between the blue and the green sectors which may be placed at 5000 \AA . The three others are hemeprotein complexes which are of the same chemical nature but are in three different states of oxidation. These enable us to perceive respectively the green, yellow and red sectors of the spectrum. That the absorption spectra of these pigments overlap is evident from the fact that we observe a continuous sequence of colour in which intermediate colours between green and yellow and between yellow and red are readily recognisable. Within the wavelength range between 5000 \AA and the extreme red end of the spectrum, monochromatic light is perceived with a colour which varies with its position in the spectrum and is determinable with considerable precision. Such precision is highest in the wavelength range around 5800 \AA which is the centre of the yellow region in the spectrum.

We shall first consider the simple cases in which the incident light contains only two monochromatic components. Here again, we have to distinguish between different possibilities. Both spectral components may fall within the spectral range in which *only* the carotenoid pigment functions or *only* the *heme* pigments. The third case is that in which one spectral component is perceived with the aid of the carotenoid pigment and the other through the agency of the *heme* pigments.

It is clear that this third case is on a different footing from the other two.

The carotenoid pigment consists of long-chain molecules the absorption spectrum of which exhibits three well-defined maxima of which the position varies a little with the solvent employed. For the particular case in which the solvent is ethanol, they have been located at 476, 446.5 and 420 $m\mu$ respectively, the three peaks together covering the wavelength range between 500 and 400 $m\mu$ in which the absorption is most conspicuous. The wave-number differences between the absorption peaks are of the same order of magnitude as the vibrational frequencies associated with the ethylenic bonds present in the molecule. We are therefore justified in assuming that the absorption spectrum represents the result of a combination of an electronic transition with vibrational transitions. Whether this be the case or not, it is clear from the form of the absorption curve that the molecule can exist in different energy states between which transitions can occur. It accordingly becomes necessary to consider such transitions as a possible part of the process occurring in the retina.

If ν_1 and ν_2 be the frequencies of the light incident on the retina, the corpuscular energies are given by $h\nu_1$ and $h\nu_2$ respectively. We shall assume that ν_1 and ν_2 correspond to wavelengths both greater than or both less than 5000 Å. Not all the corpuscles of these energies incident on the retina would be absorbed and contribute to the perception of light. If the numbers which are actually so effective are in the proportion of N_1 to N_2 during any small interval of time, the total energy available in that interval would be $N_1h\nu_1 + N_2h\nu_2$. If N_1 is large compared with N_2 , there would clearly arise the possibility that only the more intense component would be perceived and that the weaker component would be masked or suppressed. But if N_1 and N_2 are comparable with each other, the sensory mechanism would find it possible to perceive both the spectral components but not separately. It would perceive the mixture as monochromatic light of frequency equal to

$$(N_1h\nu_1 + N_2h\nu_2)/(N_1 + N_2)h,$$

in other words, as light having a frequency which is the weighted average of the frequencies of the individual components.

We shall next consider the cases in which one of two spectral components has a wavelength less and the other a wavelength greater than 5000 Å. As a consequence, both kinds of visual pigment function. Here, again, there is the possibility that one of the two spectral components in the light may mask the other and prevent its being perceived. But in the present case, the two components can influence each other in such manner as to modify the nature of the resulting sensation and make it quite different from what either of them by itself would produce. Such modification would arise by reason of a transfer of part of the corpuscular energy from one of the spectral components to the other, the transfer being made possible by the two pigments being in actual physical

contact with each other. The carotenoid pigment can exist in various energy-states represented by light of wavelengths over the range from 4000 to 5000 Å. It can therefore either take up or give up energy so as to pass from one state to another during the process which results in the perception of light and colour. The energy thus taken up or given up would pass from one spectral component to the other. We may represent this process as below:

$$h\nu_1 + h\nu_2 \rightarrow h\nu_1^* + h\nu_2^*.$$

Here ν_1 and ν_2 are the frequencies of light in the incident radiation having shorter and longer wavelengths respectively, while ν_1^* and ν_2^* are the frequencies of the light as actually perceived. Since we are concerned with a transfer of energy, the two sides of the equation are equal, and hence

$$\nu_1 - \nu_1^* = \nu_2^* - \nu_2.$$

In other words, when ν_1 diminishes, ν_2 increases by an equal amount of *vice versa*. The magnitude of the energy transferred may vary within the limits set by the absorption spectrum of the carotenoid pigment. Hence the radiations actually perceived would not be the incident monochromatic components, but would each consist of wide spectral bands of frequency. Indeed, in particular cases, the spectral bands covered by ν_1^* and ν_2^* may together make up the entire visible spectrum.

The sensation resulting from the superposition of the two monochromatic radiations would thus depend greatly on their positions in the spectrum and especially on their intensities. Either of them may mask the other and prevent its being perceived, if it be of sufficient intensity. But if they are of comparable strength, the perceived colour would depend on the relative strength of the spectral bands of frequency into which the two components are perceived as spread out. In particular cases, the resulting sensation may even be perfectly achromatic.

Observational proof: The remarkable result indicated by the foregoing theory that changes in the frequency of the incident radiations occur in the retina and determine the perceived colours readily admits of demonstration by quite simple methods. The most convenient light-sources to use for such observations are respectively a sodium vapour lamp and a mercury arc. The former gives yellow light of wavelength λ 5893 without any need for filtration. Two sheets of blue glass held together can isolate the λ 4358 radiation of mercury, completely excluding the green and yellow rays which are its accompaniments. Diffusing screens of ground-glass placed before the sources enable us to view them without discomfort as extended areas of illumination exhibiting their respective colours. Merely by moving the sheets of ground-glass nearer to or further away from the light-sources, large variations in brightness of these areas can be

obtained. The visual superposition of the colours may be effected by the simple device of a plate of glass held at an angle by the observer who then views the reflected image of one source against the background of illumination provided by the other source.

When the superposed fields of illumination are of comparable brightness, one of them being of orange-yellow colour and the other a deep blue, the field of superposition appears of a beautiful rose-red colour, thereby clearly showing that the frequency of the yellow light has been shifted down, transforming it into red light. The shift in the opposite direction needed to transform the yellow light into green light has to be larger than the shift downwards needed for its transformation to red light. It is therefore not surprising that in the resulting sensation the red predominates and that together with the blue of the mercury source, gives a rose-red sensation.

It should be mentioned that if in the observations, the blue is set at a sufficiently high intensity, it completely masks the yellow which is then not perceived. Likewise, if the yellow is set at a sufficiently high level of brightness, it completely masks the blue which is then not perceived. There is also an intermediate stage where the rose-red appears of a paler hue approaching an achromatic sensation.

Similar observations can also be made using two mercury lamps as the sources, one to give the λ 4358 radiation, and the other with a suitable filter to isolate the green λ 5461 rays. It is found that when the relative brightness of the two superposed radiations is correctly adjusted, the result is a perfectly achromatic sensation. If one or the other is in excess, the field of superposition exhibits a bluish or a greenish tinge respectively.

The colours of superposed spectra: A very simple technique has been devised and used by the author which yields results of great interest. The principle of the method is that the observer sees simultaneously two spectra of white light dispersed to the same extent, but superposed in positions which are displaced with respect to each other, so that the regions which overlap can be varied at will. It is desirable that the brightness of the spectra can be varied so that they can be of equal intensities, or one of them can be brighter and the other feebler as desired. With these arrangements, the observer sees the effect of superposing monochromatic light of two different wavelengths in various regions of the spectrum simultaneously. The wavelength differences and the regions of the spectra in which the superposed radiations are located are adjustable as desired. It is very useful so to arrange matters that strips of the two superposed spectra remain visible above and below the region of overlap, so that the observer can see at a glance what the colours superposed actually are in the region under view.

The author has found it convenient in practice to use two independent sources of white light, as for example, two luminous tungsten-filaments held parallel to each other and at a suitable distance apart, and to view the diffraction spectra of the first-order of these sources through a replica grating held before the observer's

eye. By varying the distance apart of the two sources or by the observer moving towards or away from them, the spectra can be seen superposed in various positions relative to each other. By adjusting the heating current passing through one of the filaments, the relative brightness of the superposed spectra can be altered as desired. It is easily arranged that the two spectra which overlap along their length in the middle of the field can be seen separately above and below it.

The boundary between the blue and green sectors of the spectrum which overlaps the other appears as a sharply defined line of separation between regions exhibiting totally different colours. Particularly striking effects are noticed when the blue sector of one spectrum overlaps the regions in the other which exhibit colours ranging from yellow to orange. The region of overlap then exhibits a brilliant rose-red colour wholly unlike the other colours of the spectrum. An effort has been made to reproduce this effect in the colour-sketch appearing in plate VI*.

It is possible also to study the results of superposing the blue sector of one spectrum on various other regions in the second spectrum, as for example, on its green sector, though the effects are, in these cases, of a less striking character. It is likewise possible to observe the effects of superposing the red, yellow and green of one spectrum on these colours in the other spectrum. Such effects are noticeable if the superposed colours are of comparable intensities. But if they are of different orders of brightness, the more luminous sector suppresses the weaker one, its own colour remaining apparently unaffected.

Studies with two monochromators: Another technique for the study of the superposition of spectral colours employs two spectrographs of the well-known type in which the spectra can be displaced by a rotation of the dispersing prisms. The eye-pieces of the observing telescopes are removed and adjustable slits are placed in the focal planes through which limited regions of the spectra can emerge. Enlarged images of these slits are projected on a sheet of ground-glass so as to coincide for the most part, leaving areas on either side of the region of overlap so that the colours which are superposed can also be individually perceived. Tungsten-filament lamps of high wattage of the kind used in projection lamps are placed close to the slits of the spectrographs, thereby ensuring the formation of spectra of adequate brilliance in the respective focal planes. The ground-glass sheet on which the patches of colour appear is viewed by the observer from a comfortable distance. By rotating the drums, any two desired locations in the spectra can be seen superposed on each other. By opening or narrowing the collimator slits, their relative brightness can also be varied.

Observations by this method confirm and usefully supplement the results obtained by the other methods. They establish the conclusions already set forth

*For plate VI, see p. 592.

and make it evident that the synthesis of colour is effected by the processes which have been discussed in detail in this chapter. It may be remarked that the superposition of light from the two extreme ends of the spectrum or near thereto results in the perception of a rose-red colour over a wide range of the relative intensities of the red and the violet which are thus superposed. Outside this range, only one or the other of the two colours is perceived, the brighter colour masking the feebler.

CHAPTER XIX

Colours of physical origin

The basic facts and principles relating to the perception of the colours of composite light have been set forth and established in the preceding two chapters. It is however not without interest to consider various actual cases of importance and to show how they illustrate the ideas regarding the composition of spectral colours expounded in this book. There are, of course, a great variety of such cases which could be discussed and dealt with. Colour plays an enormously important role in human life and activity, and the production of materials exhibiting colour is a substantial part of human industry and of scientific technology. The dyeing of textiles may be mentioned as an outstanding example of the kind. Such activities create a demand for the precise specification of colour and for methods by which colour exhibited by various materials can be subjected to precise comparison and measurement. A further consequence of the interest in colour is the demand for the reproductions of colour by special techniques and especially by photography and the wide dissemination of such reproductions by the art of colour printing. To deal with the fields indicated above in their entirety from the standpoints adopted in the present work would need more than one treatise. We shall, therefore, restrict ourselves to the consideration of some leading cases and to some topics of special importance.

The colours of interference: The general nature of interference patterns and their appearance as seen by monochromatic light were described in Chapter II. They were discussed in greater detail in Chapter VII. Methods for producing them on a large scale so that they could be conveniently observed and studied without optical aid were also indicated in that chapter. We shall here consider rather more fully the explanation of the chromatic features of such patterns when observed in white light, since they are an excellent illustration of the production of colour by purely physical methods. The colours of interference arise by reason of the intensity of the light reflected by the thin films which exhibit such colours being dependent on the wavelength, and hence different for the different parts of the spectrum. It is obvious that the relative luminosity of the different colour regions in the spectrum would play a highly important role in determining the visible result of superposing the interference patterns due to light of different wavelengths. Since the interferences for any particular wavelength consist of areas on the film which are alternately dark and bright, it is to be expected that the pattern

as observed with white light would exhibit a series of maxima and minima of illumination, the positions of which would be determined by the wavelength of the most luminous part of the spectrum. This is actually the case and the measurements of these positions set out in Chapter VII showed that the effective wavelength is close to the wavelength of the yellow light of the sodium vapour lamp, and quite outside either the green or the greenish-yellow part of the spectrum.

A very convenient procedure for exhibiting the role played by different colour sectors of the spectrum in interference patterns is to view them through colour-filters of different sorts. We may begin by considering the blue sector of the spectrum which lies in the wavelength range between 400 and 500 $m\mu$. Since it is the least luminous part of the spectrum, it is not to be expected that it would make any sensible contribution to the observed colour-sequence except in those regions where the rest of the spectrum is present with low intensities. This is actually the case. On viewing the pattern through a yellow plate of glass which cuts out the blue completely and leaves the rest of the spectrum unaffected, it is found that no change is detectable anywhere, except in two narrow strips contiguous to the two most conspicuous minima of intensity in the white light patterns. Here, the observed colour changes on the introduction of the filter from a blue or a bluish-green to a clear green.

A plate of red glass which cuts out all wavelengths less than 600 $m\mu$ is effectively a monochromatic light filter. The interference pattern as seen through it exhibits a large number of dark bands alternating with bright bands. Two sheets of green glass put together which transmit only the region between 500 and 560 $m\mu$ behave likewise. The difference between the effective wavelengths in the two cases results in a contraction of the pattern when we change from the red filter to the green filter, all the bands moving in the same direction to their new positions. It is easy to compare the positions of the colour bands in the white light pattern with the positions of the dark and bright bands as seen respectively with the red and the green colour-filters. It is then found that the red bands as seen with white light coincide in position with the dark bands as seen with the green filter. *Vice versa*, the green bands in the white light pattern coincide with the dark bands as seen with the red filters. Their positions in both cases are adjacent to the positions of minimum illumination in the white light pattern, but in the two cases appear on opposite sides of those positions.

These observations make it evident that the manifestation of colour in the white light patterns results from the red or the green sector of the spectrum (as the case may be) masking or suppressing the perception of all the other colours of the spectrum which appear with low intensities. Such masking becomes incomplete as we proceed to the higher orders of interference and the minima of illumination in the pattern fade away as a consequence.

Interesting effects are observed when the white-light interference patterns are viewed through a plate of glass which has been doped with neodymium oxide.

This filter totally absorbs the wavelength range between 570 and 600 $m\mu$, in other words excludes the yellow sector, while the green and the red sectors come through freely. The introduction of this filter before the eye results in a large increase in the number of interferences visible and the pattern then covers the whole field. But the different areas show quite different features. The exclusion of the yellow results in the first few bands exhibiting highly saturated reds and greens with sharply defined boundaries between the contrasted colours. We have next a succession of five alternately dark and bright bands which are practically achromatic. Beyond this again, we have a succession of bands exhibiting colours but in the reverse order and much less saturated.

These effects arise by reason of the suppression of the yellow sector. The result is that the pattern then represents a superposition of two sets of interferences due to the red and green sectors of the spectrum, the bands of which are spaced differently. That the colour bands show sharply defined boundaries is a demonstration that the observed effects arise from a masking of the weaker by the stronger colours and not from an additive composition of colours.

Some interesting features are also observed when the interference patterns are viewed through an orange-coloured plate of glass which cuts out all wavelengths less than 540 $m\mu$. Many more bands can be seen than are visible with white light, and the minima of illumination in the pattern are also more conspicuous, at least six of them being clearly seen. The first few rings show the yellow colour at the maxima of illumination. All the other bands in the pattern appear alternately green and red, these areas of colour being sharply defined and of equal width.

Fraunhofer diffraction patterns: Colours having a purely physical origin are also observed when a brilliant source of white light of small extension is viewed by an observer holding before his eye an opaque screen pierced by tiny apertures through which light can find entry. Particularly striking effects are produced if these apertures are numerous and are arranged in a regular two-dimensional array and thus form what is usually referred to as a diffraction grating. Such a grating disperses light of different wavelengths in different directions, thereby resulting in the formation of what are known as diffraction spectra. We are however not concerned here with such spectra, but with the diffraction patterns of individual apertures in which the effects produced by the various wavelengths in the continuous spectrum of white light overlap and thereby give the colours of composite radiation. For our present purpose, it will suffice to consider the best known and indeed the simplest of all such patterns, viz., the case of a linear source of white light viewed through a narrow slit bounded by sharp parallel edges.

The nature of the diffraction pattern resulting from the passage of light through a long slit with parallel edges is well-known. It consists of a series of parallel bands, the central band being twice as wide as those on either side of it. If the observations are made with monochromatic light, the bright bands are separated from each other by a series of equally-spaced dark lines appearing on each side of

the pattern. The central band is the brightest of all, while the successive bands on either side of it fall off progressively in brightness. The angular spread of the pattern is proportional to the wavelength of the light, the nature of the pattern however remaining the same.

It is worthy of remark that the minima of illumination in the white light patterns are conspicuous, the first two on each side being almost perfectly dark. The disposition of the colours seen in the white light patterns is very clearly related to the positions of these minima of illumination, four of which are clearly seen. Measurements of the positions of these minima with a source of white light and also with sodium light show a close agreement. The situation is thus analogous to what has been observed in the patterns of interference and set out fully in Chapter VII. The sequence of colour seen in the diffraction pattern resembles that noticed in the interference pattern of a wedge-shaped film of air. We need not therefore discuss it here further.

The colours of rotatory dispersion: The property exhibited by plates of quartz of rotating the plane of polarisation of light traversing the crystal along its optic axis provides a simple and very useful method for the study of the colours of composite light. A plate of quartz 1 mm thick and cut normal to the optic axis rotates the plane of polarisation by 15° of arc at the red end of the spectrum increasing to 50° at the violet end. If an extended source of light is viewed through the plate held between two crossed polaroids, the rotation results in a restoration of the light, but this can be extinguished for any particular region of the spectrum by turning one of the polaroids with respect to the other so as to compensate for such rotation. If the spectrum of the light coming through along the optic axis is examined through a spectroscope, it will be found to exhibit a perfectly dark band crossing it at the wavelength at which the light is extinguished, while on either side, the spectrum remains visible. The position of the band of extinction is observed to shift when one of the polaroids is rotated. It can therefore be set so as to place the extinction in any desired region of the spectrum. The colour of the light emerging through the polaroids and the crystal in the axial direction can then be observed and its relation to the part of the spectrum which is extinguished can be determined.

A plate of quartz 5 mm thick is very convenient for the observations. The difference of the rotations at the two ends of the spectrum does not then exceed 180° of arc, and hence there is only one band of extinction to be seen in the spectrum, and by setting the polaroids suitably, this can be moved from one end of the spectrum to the other. The varying colour of the light emerging in the axial direction can then be followed. Thinner plates of quartz may also be used and the region of extinction in the spectrum may likewise be moved from one end of it to the other. But the effective width of the spectral band of extinction would then be greater. This may be an advantage in certain cases. Such observations enable us firmly to establish various propositions which are fundamental in the theory of

colour perception and which we shall now proceed to consider.

A colour which is well-known and easily recognised is that which goes by the name of purple. Already in Chapter XVII it has been shown by observations on the light transmitted by aqueous solutions of certain dye-stuffs that the purple sensation is perceived when the yellow sector of the spectrum has been eliminated by absorption, while the red, green and blue sectors of the spectrum appear with full strength. This result receives an independent confirmation from studies on the colours of rotatory dispersion. Observations with quartz plates of various thicknesses ranging from half a mm to 6 mm show that when the polaroids are so set that the colour of the transmitted light is purple, the spectroscope reveals that a band of extinction covers the yellow sector of the spectrum while the red, green and blue continue to be visible.

That the yellow sector is the most luminous part of the spectrum at ordinary or daylight levels of illumination is made evident by the same observations which show that its extinction results in the rest of the spectrum being perceived as purple. The setting of the polaroids which results in the axially transmitted light being perceived to be of purple hue is also the setting at which the transmitted light has the minimum visual brightness. Rotating one of the polaroids away from the correct setting in either direction results in a rapid change of the colour of the transmitted light and it also results in a large increase in its luminosity.

The foregoing remarks may be very prettily illustrated by using plates of quartz which are less than a mm thick. Held between the two polaroids and viewed against an extended source of illumination, a dark cross is observed in the field when the light which comes through is nearly at its minimum of intensity. This cross at one setting of the polaroids appears blue in colour and at a slightly different setting of a reddish hue. There is an intermediate setting at which the transmitted light is extremely feeble. The dark cross then exhibits a purple colour. But it requires a very bright field of illumination for this colour to be seen and recognised. It may be remarked that at this stage, the light of a sodium vapour lamp is extinguished when viewed in the axial direction through the crystal and the polaroids.

An important question concerns the colour which is complementary to green. In other words, if the green is excluded from the spectrum while the red, yellow and blue sectors are in full strength, what is the colour that is perceived? This question can be readily answered with the aid of a quartz plate which is 5 or 6 mm thick. The polaroids are set so that the colour of the light emerging in the axial direction is purple. Spectroscopic examination shows that the yellow of the spectrum has then been extinguished. One of the polaroids is then turned round so that the band of extinction moves from the yellow well into the green and is at the centre of the green sector. The yellow and red sectors as well as the blue sector are seen quite brilliantly, while the green is almost entirely cut out from the spectrum. The transmitted light appears of a rose-red hue which is thus the complementary colour to green.

A block of colourless quartz 15 mm thick with polished faces normal to the optic axis and held between crossed polaroids exhibits the colours of rotatory dispersion quite conspicuously when viewed against a bright field of illumination. The pattern consists of concentric rings of colour around a coloured centre, the rings being alternately green and rose-red. A noteworthy feature observed in these patterns is that the bands of contrasting colour have sharply defined boundaries separating them from each other. The positions of these boundaries coincide with the lines of zero intensity in the same patterns as seen with the monochromatic light of a sodium lamp. A block of this thickness exhibits three bands of extinction in the spectrum of the light which has traversed the crystal along its optic axis. The change in the colour of the transmitted light occurs when one of the bands of extinction passes over from the red to the green sector in the spectrum.

The blue sky: On a clear sunny day and especially after a shower of rain has washed out all dust and haze from the atmosphere, the sky exhibits a blue colour of remarkable depth and purity. In these circumstances, the origin of the light which reaches us and exhibits this colour is evidently sunlight which has been scattered by the gaseous molecules of the atmosphere, the shorter wavelengths having gained in intensity relatively to the longer wavelengths in the spectrum in the process of such scattering. But it is not to be supposed that in the spectrum of skylight, the blue sector is the most luminous part. This is very far indeed from being the case, as becomes evident when the blue sky is viewed through a filter of yellow glass which cuts out the blue but has no influence on the rest of the spectrum. It is found that the filter has little or no observable effect on the brightness of skylight, though its colour is altered to a greenish-yellow. In other words, the blue contributes very little to the luminosity of the sky. When then, it may be asked, does it determine its observed colour?

The answer to this question, in other words, the real explanation of the blue colour of the sky is that it is a consequence of the masking or suppression of all the other colours in the spectrum by its blue sector. In Chapter XVII, we have already noticed that such masking may be demonstrated with the aid of a dilute solution of cuprammonium. Adding water to this solution contained in a cell which is 2 cm in depth, the spectrum of the light transmitted by the cell may be progressively extended so as to cover, besides the blue sector, also the green, yellow and red sectors, in other words, the whole of the spectrum. In this process, the intensity of the light which passes through the cell increases rapidly. But so long as the yellow and red sectors exhibit an appreciable diminution of their intensity relatively to the blue sector, the colour of the transmitted light remains a clear blue.

This remarkable power of the blue sector to suppress the perception of the other colours in the spectrum finds its explanation in the visual processes described and discussed in Chapter XVIII. The superposition of blue light on

monochromatic light appearing in any other part of the spectrum results in spreading it out over a wide spectral range of frequencies and thus destroying the specificity needed for the perception of colour. Not much of blue light is needed to carry this process to completion. The surplus of blue light left over is perceived and determines the observed colour.

The colour of oceanic waters: Great bodies of clear water illuminated by sunlight which penetrates into their depths exhibit a colour resembling the blue of the sky but much superior to it in respect of its saturation. The origin of this phenomenon was investigated by the author and his conclusions were set out in a memoir published in the *Proceedings of the Royal Society of London* for April 1922 under the title of "The Molecular Scattering of Light in Water and the Colour of the Sea". The subject was there discussed in great detail and with a certain measure of completeness. For our present purpose, it is sufficient here to mention only the essential points in the explanation of the phenomenon and the differences between it and the case of the blue of the sky considered in the foregoing paragraphs.

The molecules of water scatter sunlight traversing the liquid to a readily observable extent. Indeed, such scattering is much more powerful than the scattering of sunlight by an equal volume of the gases of the atmosphere, though not as powerful as could be expected in view of the greater density of the material. The restriction of freedom of movement of the molecules in a liquid accounts for this fact. But there is another important difference between the two cases. The atmosphere of the earth may be regarded as transparent to light within the range of the visible spectrum. Water, on the other hand, has a weak absorption arising from the overtones of the characteristic infra-red frequencies of molecular vibration. Such absorption, though weak, is sufficient to reduce very considerably the intensity of the red and yellow in the light emerging after internal scattering from inside a great depth of clear water. Hence, the red and yellow sectors are much weaker relatively to the blue than in the case of the scattering of sunlight by the gases of the atmosphere. The masking by the blue of all the other colours of the spectrum is therefore quite complete. What is accordingly perceived is only the blue end of the spectrum.

CHAPTER XX

The colours of foliage and flowers

We are concerned in the present chapter with the colours exhibited by foliage and by flowers *in vivo*. These are the colours which we actually perceive and it is their relationship to the spectral character of the light reaching our eyes which is the subject of study. Sunlight is incident on the leaves of growing vegetation or on the petals of the flowers. It enters the material and re-emerges after internal diffusion or scattering. It may also be accompanied by light which is reflected or diffused at the surfaces of the leaves or petals. Such reflections disturb the observed colour. But they are usually not important and their effect can be minimised by an appropriate choice of the direction of observation. They may be completely avoided if the light which emerges after passing through the leaf or flower is examined. Most leaves and flower petals are thin enough to allow sufficient light to emerge in this manner which could be observed visually through a pocket spectroscope containing a wavelength scale. The regions of the spectrum in which there is strong absorption can be recognised, and this may be supplemented by visual comparison of the spectrum with the spectrum of daylight diffused by a matt white surface.

In many cases, immersion of the leaves or petals in a glass vessel containing a suitable organic solvent, as for example, acetone, enables the pigments responsible for their colour to be quickly extracted. The extract may then be transferred to an observation tube of suitable length which is held against a brilliant source of white light. The spectrum of the light coming through the tube can be examined visually. Spectroscopic examination of such extracts is useful in some cases, as for example, when the colour of the flower is so deep as to obscure the nature of the absorption spectrum. Diluting the extract or using a smaller depth of the absorbing column is then helpful.

Extensive studies carried out by the author using these techniques have enabled a comprehensive view to be obtained of the nature of floral colours and of their relationship to the absorptive properties of the pigments contained in the material of their petals. Perhaps the most interesting discovery made in the course of these studies is that in many cases, the light emerging from the petals exhibits a series of discrete absorption bands which are usually three in number. These bands appear in the region of wavelengths between 480 and 650 m μ . Their positions and the strength of the absorption in the different bands determine the observed colour of the flowers. There is no difficulty whatever in obtaining

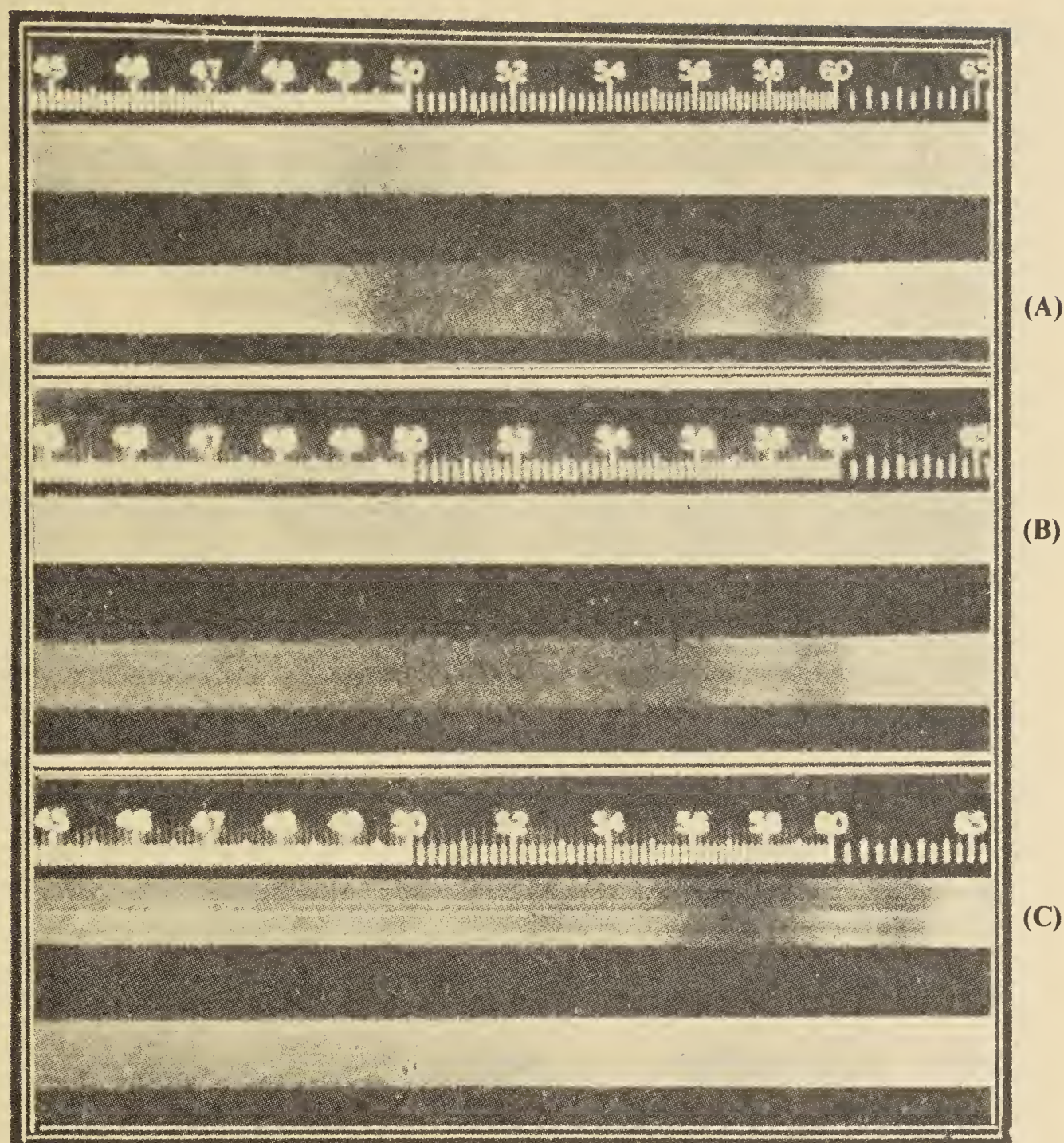


Figure 9. Absorption spectra of flowers. (A) *Spathoglottis plicata* (B) *Purple cineraria* (C) *Clitoria ternata*.

Plate VII

photographic spectra accompanied by wavelength scales which exhibit these bands in a conspicuous fashion. Many such spectrograms have been obtained and a selection from them has been reproduced with this chapter. They help to show clearly how the observed colour of the flowers is related to the spectral character of the light emerging from their petals.

The colour of green leaves: The most familiar amongst all colours of biological origin and therefore the first to claim our attention is that exhibited by the foliage of living and growing vegetation. Its spectral nature can be studied in the open air on a large scale. An impressive demonstration of that colour is furnished by the fields in which rice-plants are grown under irrigation. Directing a pocket spectroscope obliquely downwards in the direction at which the colour is seen at its best, the spectral nature of the light exhibiting the colour becomes evident, and

this can be compared with the spectral nature of the light of the sky. The spectrum of skylight extends over the entire range from 400 to 700 $m\mu$. The luminosity of the sky is naturally much higher than that of the green carpet of the rice-fields. But this does not stand in the way of the essential differences in the character of their spectra being recognised. The first and most obvious difference is the complete extinction of the blue-violet sector between 400 and 500 $m\mu$ in the green colour of the vegetation. Another noticeable difference is the contraction of the red sector, which instead of extending to about 700 $m\mu$ is unobservable beyond about 640 $m\mu$. But the part of the spectrum between 590 and 640 $m\mu$ where the orange and the red appear continues to be visible and is not noticeably weakened in relation to the rest of the spectrum. The most significant difference between the two spectra is, however, the nearly complete extinction of the yellow sector in the spectrum of the green light. The spectral range between 560 and 590 $m\mu$ appears indeed much dimmer than the green and red sectors on either side of it, instead of being, as it normally is, the brightest part of the solar spectrum. By reason of the drop in brightness on either side of it, the green sector stands out conspicuously.

It is very instructive to examine the leaves of a plant which are in the successive stages of development, commencing from the tender leaf which has a pale greenish-yellow hue and proceeding by steps to the mature leaf exhibiting a full green colour. It then becomes evident that the progressive change of colour is the result of a more complete elimination of the yellow sector of the spectrum between 560 and 590 $m\mu$. In other words, for the green of the leaf to be manifested in its full strength, the extinction of the yellow region is essential. With the mature leaves, the fraction of the light which comes through is considerably smaller. This reduction shows itself in a diminished brightness of every part of the spectrum. But much of the weakening is due to the more complete extinction of the yellow region which in the case of the immature leaves is quite luminous and in the mature leaves is not at all discernible.

Even the fully developed leaves of different plants and trees exhibit a wide range of variation in the colour and luminosity which they exhibit. The leaves of some trees, as for example, the well-known fruit-bearing *Artocarpus integrifolius* are of a very dark green colour when mature, though in the earlier stages of their development, they exhibit brighter colours. Spectroscopic examination reveals that the range of wavelengths of the light which filters through the leaf remains much the same, viz., from 520 to 640 $m\mu$, though the intensity of the light is very much reduced in the case of the mature leaves. What is particularly interesting is that the part of this spectral range in which the orange and the red appear is visible with the leaves in all stages of development. We are obliged to conclude from this that the green of the spectrum has the effect of masking the red and orange, in other words, prevents them from being perceived.

The colour of growing vegetation owes its origin to the pigments which partake in the photosynthetic activity. These materials can be extracted from the leaves by immersion in organic solvents, the most suitable and effective of them being

acetone. Placing the acetone extract in a flat glass cell, the colour as seen by transmitted light and its relation to its absorption spectrum can be readily ascertained. A striking demonstration of colour changes entirely analogous to those exhibited by the leaves of plants in the course of their development can be given with the aid of the extracts. For this purpose, a glass cell is filled to about a third of its depth with pure acetone, and the acetone extract which is itself of a dark green colour is then added a little at a time. The acetone in the cell first turns yellow, then to a greenish-yellow and then progressively to a clear green. These changes correspond to the alterations in the character of the absorption spectrum of the liquid contained in the cell. A cut-off of the red beyond $640\text{ m}\mu$ appears at the very outset, and this is soon followed by the extinction of the blue upto $500\text{ m}\mu$. But not until a band of absorption in the yellow between 570 and $586\text{ m}\mu$ manifests itself in the spectrum and is fully developed does the solution exhibit a full green colour.

The absorption spectrum of the pigments present in the green leaves can be observed with the leaves themselves. For this purpose, it is best to use a leaf of dark-green colour as for example, the mature leaf of *Artocarpus integrifolius* through which very little light can normally filter through. It should be held close to the very brilliant source of white light provided by a tungsten-filament lamp of high wattage. The light which then emerges through the leaf may be viewed through a pocket spectroscope. The well known absorption bands due to chlorophyll *a* and chlorophyll *b* appearing near the red end of the spectrum can then be seen and recognised. An absorption band in the yellow region between 570 and $586\text{ m}\mu$ is also very clearly seen. Further, two *bright* bands located, one in the green between 550 and $570\text{ m}\mu$, and the other in the orange between 586 and $613\text{ m}\mu$ are also noticeable. These two bright bands are also seen in the absorption spectra of the acetone extracts of the leaf pigments.

The explanation usually given of the green colour of leaves is that it is due to the presence of chlorophyll in the leaves. This explanation needs to be qualified and supplemented by the remark that the colour is not ascribable to the characteristic and intense absorption by chlorophyll manifested near the red end of the spectrum. For, the luminous efficiency of this region is very low and the presence or absence of absorption in it can make little difference to the observed colour of the leaves. Actually, as we have seen, the colour is ascribable to the absorption of the yellow sector of the spectrum which is necessary to allow the green sector in the transmitted light to manifest itself to perception. The total extinction of the blue sector in the spectrum also plays an essential role. In this absorption the carotenoid pigments also participate.

The aster and its varied colours: Asters are very attractive flowers by reason of the rich and varied colours which they exhibit. The flowers appear in bunches at the end of long leafy stalks, each flower consisting of a great many petals grouped around a common centre. The material commercially available at Bangalore

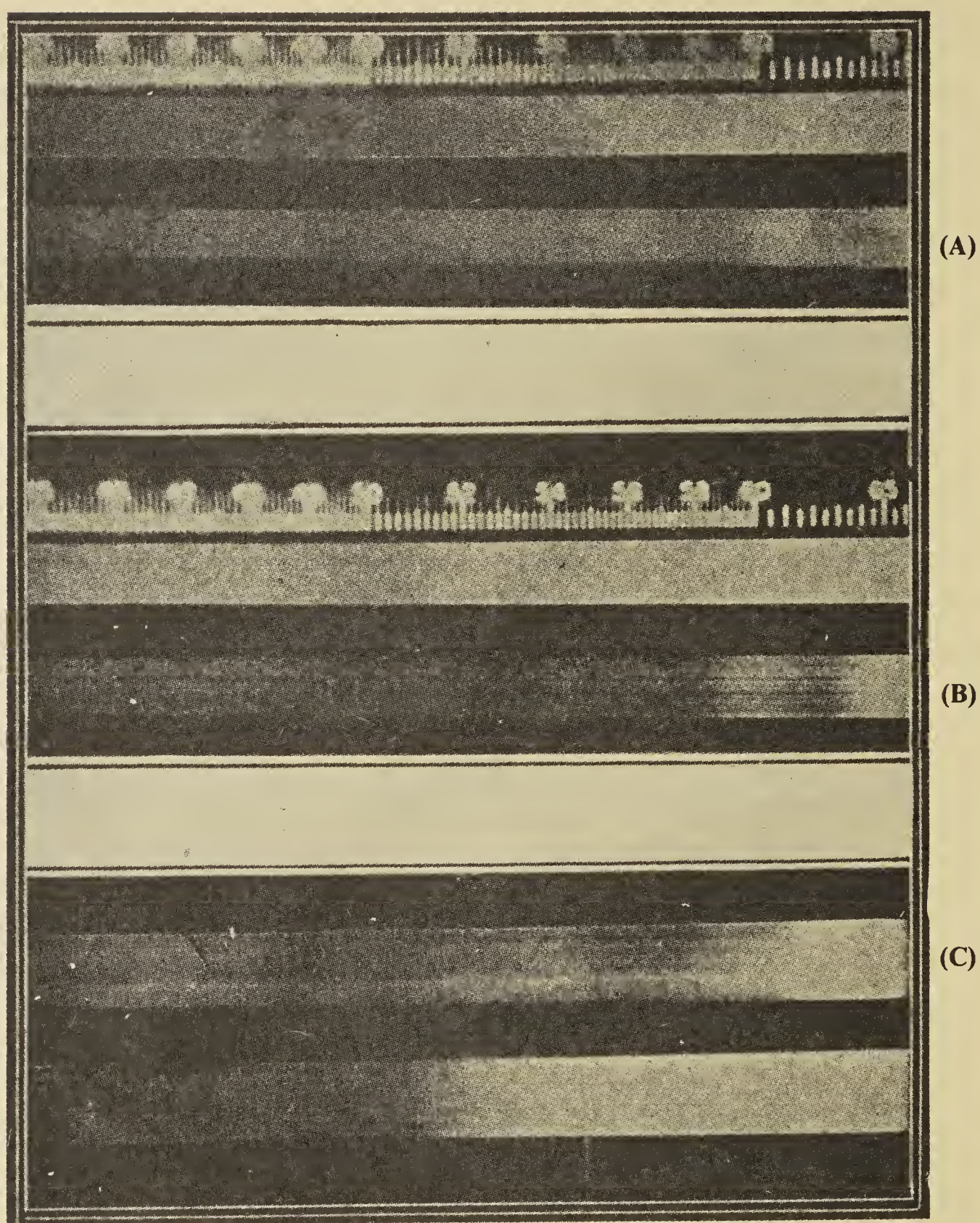


Figure 10. Absorption spectra of flowers. (A) Delphinium. (B) Lobelia. (C) Blue cornflower.

Plate VIII

includes a range of colours which fall into two groups. One group ranges in its hues from different shades of purple to a deep violet. Another group ranges in colour from a pale pink to a full red. To study these colours, all that is necessary is to hold the flower in sunlight and view it through a pocket spectroscope. The relation between the colour and the observed spectrum then becomes apparent.

The purple asters exhibit the entire spectrum of colours except the yellow which is markedly weakened. The extinction of the yellow is nearly complete with the flowers which exhibit deeper purple shades. The violet-coloured flowers show, besides the extinction of the yellow, a considerable weakening of the green sector

and also a distinct weakening of the red sector which shows a visible bifurcation by reason of an absorption band which it exhibits. The green and red sectors, despite such weakening, continue to be visible in the spectrum, but are evidently masked from perception by the presence of the blue sector.

The pink asters exhibit all the colours of the spectrum except the green sector which shows a markedly diminished intensity. The flowers in this group which exhibit deeper shades of colour show a nearly complete extinction of the green sector. Though the blue is present in the spectrum with apparently undiminished strength, it is not perceived in the observed colour which the red dominates.

The purple orchids: An absorption spectrum of a very striking nature is exhibited by the petals of the terrestrial orchid known as *Spathoglottis plicata*. This is a hardy plant which grows readily and bears clusters of flowers at the end of long leafless stalks. Viewed either by reflected or by transmitted light, the petals which are of a purplish-red colour exhibit three well-marked absorption bands widely separated from each other. One of them extinguishes the yellow sector of the spectrum. Another appears in the green sector. The third band appears in the blue-green region of the spectrum. The rest of the spectrum does not exhibit any absorption. A reproduction of the spectrum appears as figure 9A in plate VII. By immersing the petals in acetone, the pigment is readily extracted and the solution exhibits the absorption bands in the same position as the petals themselves but with an observable change in their relative intensities. The author has observed precisely similar spectra with other orchids exhibiting a purple colour.

The spectra of blue flowers: Discrete absorption bands well separated from each other also appear in the spectra of many other flowers. One of the most striking examples is furnished by the climbing plant *Clitoria ternata*, commonly known as the Butterfly-Pea. The blue flowers of this plant exhibit three such bands. One of them appears in the red region, the second in the yellow sector, and the third in the green sector. The most intense of the three absorption bands is that which appears in the yellow. This spectrum is reproduced as figure 9C in plate VII. Immersion of the petals in acetone results in a rapid extraction of the colouring matter. The solution exhibits an absorption spectrum of the same nature as the flowers. Since it is possible to make a strong solution using several petals, the absorption observed in this manner is even more striking than that of the flowers observed direct. One can see four bright bands in the spectrum separated by three very dark bands in the positions already stated and some indication of a fourth dark band in the blue-green region of the spectrum.

Other examples of blue flowers exhibiting bands of absorption in the red and yellow sectors of the spectrum are *Delphinium* and *Lobelia* illustrated in figure 10A and B respectively in plate VIII.

The spectra of red flowers: One of the best known of garden flowers is the China

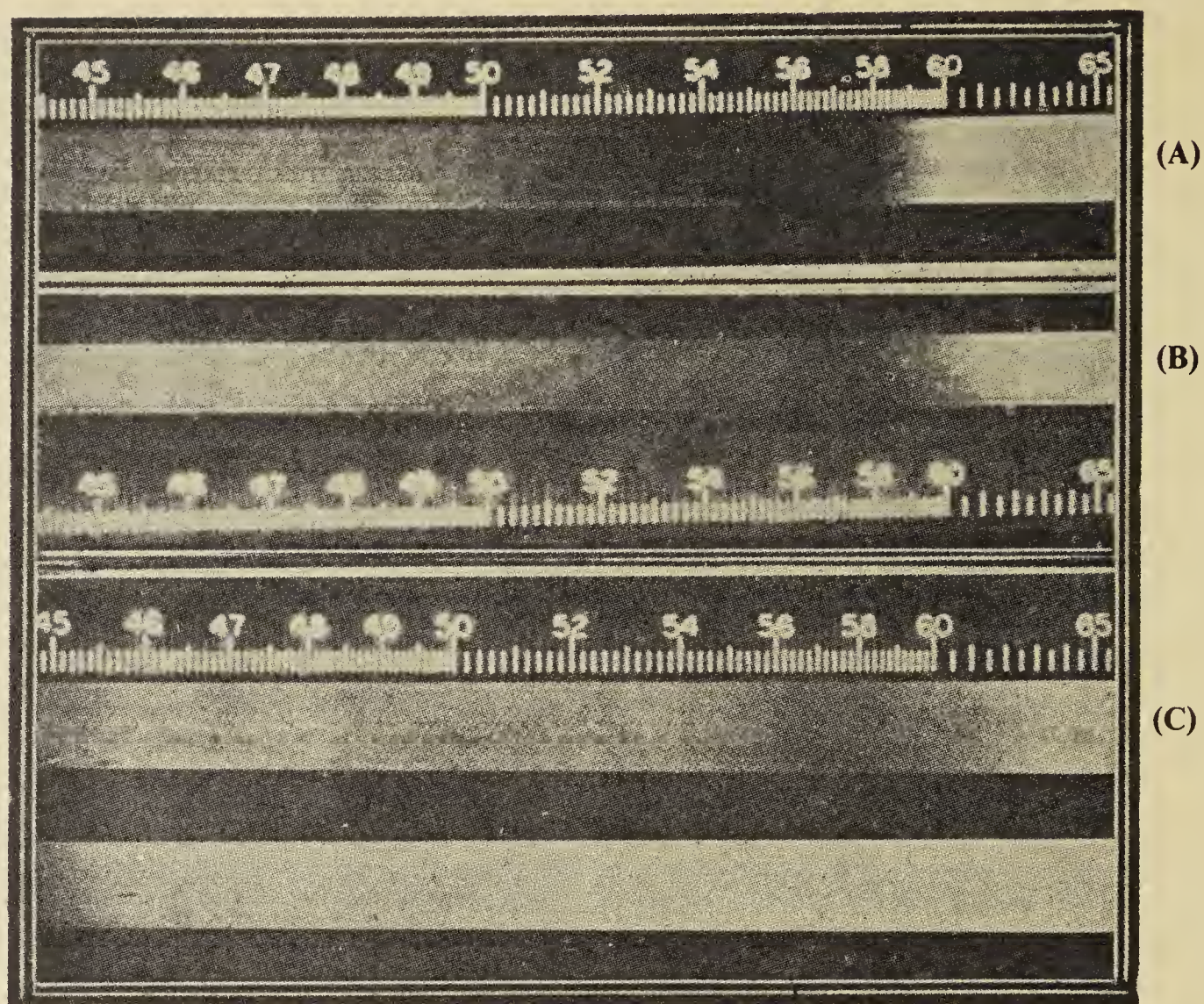


Figure 11. Absorption spectra of flowers. (A) Purple balsam. (B) African violet. (C) Morning glory.

Plate IX

Rose (*Hibiscus rosa sinensis*) which has large single blooms from which long bunches of stamens hang out. The petals exhibit a rich red hue. Spectroscopic examination shows a complete extinction of the blue, green and yellow sectors in the light which comes through them, the red sector commencing from $600\text{ m}\mu$ being in full strength in the transmitted light. The spectral characters of the floral pigment responsible for this spectral behaviour is better understood when it is extracted by the aid of acetone, leaving the petals colourless. The extract exhibits a deep red colour and an intense absorption covering all wavelengths less than $600\text{ m}\mu$. Using short absorption paths or else by diluting the extract with acetone, thereby allowing light of smaller wavelengths to come through, a strong absorption band between 580 and $590\text{ m}\mu$, reveals itself, as also another strong band between 530 and $550\text{ m}\mu$. There is also a weak absorption band at about $500\text{ m}\mu$. The blue sector of the spectrum can be seen coming through, though only weakly. If, instead of the Chinese Hibiscus, we use red or crimson roses, precisely similar phenomena are observed.

The masking of colour sensations: The examination of floral colours *in vivo* with the aid of the spectroscope makes it evident that in the visual perception of colour

it is masking and not additive superposition that plays the leading role. This is particularly obvious when we study flowers of which the perceived colour ranges from violet and dark blue to comparatively lighter shades of blue. The following may be mentioned as illustrative examples:

The *Morning Glory* is a climbing shrub of the *Convolvulus* family (known botanically as *Ipomea learii*) which bears large bell-shaped flowers of which the petals display a dark blue colour. The spectroscope reveals that this colour results from the absorption of light in the spectral region between 560 and 620 $m\mu$, in other words, of the yellow and orange in the spectrum. But there is no noticeable weakening of any other part of the spectrum. These features are evident in the spectrogram reproduced as figure 11C in plate IX.

The tree known as *Solanum grandiflorum* of which the popular name is the nightshade or potato tree, flowers profusely. The petals have a violet colour which in the course of a few days fades away and becomes nearly white. In the wavelength range between 570 and 595 $m\mu$, there is nearly complete extinction and there is a noticeable diminution of the intensity of the green of the spectrum. There are also detectable absorption bands at 545 and at 635 $m\mu$. The red and the green are alike suppressed from perception by the violet of the spectrum.

Another flower showing a deep violet colour is that of the shrub *Meyenia erecta*. Seen either by reflected or by transmitted light, the flowers exhibit three absorption bands, one at about 540 $m\mu$, a second at about 580 $m\mu$ and third at about 630 $m\mu$, these being respectively in the green, yellow and red regions. A bright band in the orange centred at 610 $m\mu$ is a conspicuous feature in the spectrum, while the unabsorbed regions in the green and the red also remain visible.

The plant of which the botanical name is *Saintpaulia ionantha* (known popularly as the African violet) is a small herbaceous perennial which bears flowers which are violet in colour. The spectrum of the light either reflected or transmitted by the flower exhibits the entire range of wavelengths from the red to the violet except the wavelength range from 520 to 600 $m\mu$ which is much weakened by absorption. The spectrum of this is reproduced in figure 11B in plate IX.

The shrub *Centaurea cyanus*, commonly known as the corn-flower, exhibits flowers of a blue colour. The spectroscope reveals that this colour is ascribable to an absorption in the yellow and orange-yellow regions in the spectrum. These features can be recognised in the spectrogram reproduced as figure 10C in plate VIII.

Plumbago capensis is a shrub which bears clusters of flowers of a pale blue colour. The absorption of light by these flowers is weak and is barely noticeable in the spectrum of the light transmitted by a single petal. But if we hold a few flowers together, the blue colour of the light which penetrates through the mass is conspicuous. Examining this light through a pocket spectroscope, an absorption band is visible in the yellow and fainter bands in the red and the green.

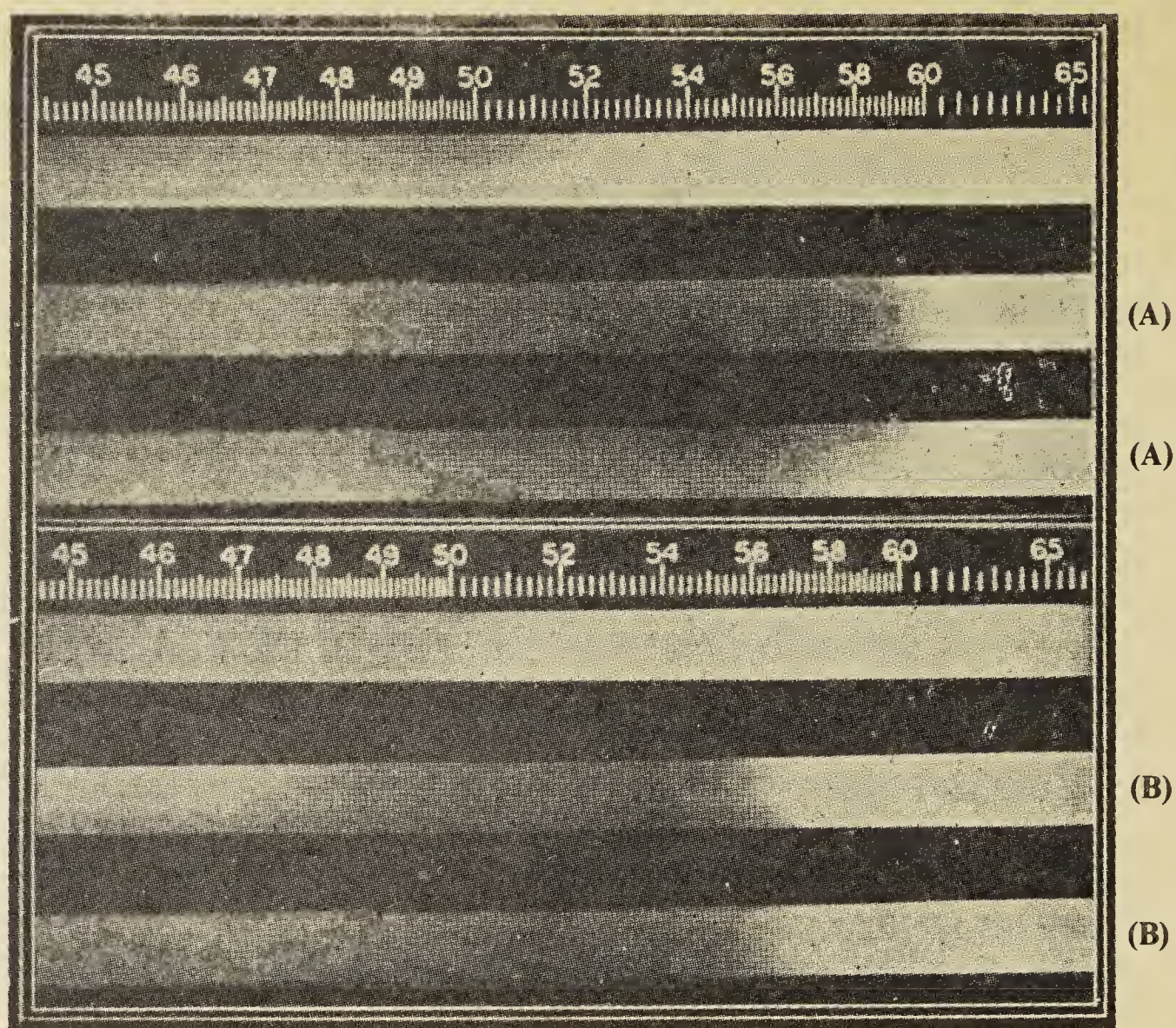


Figure 12. Absorption spectra of flowers. (A) *Lagerstroemia flos reginae* (purple). (B) *Lagerstroemia flos reginae* (rose-red).

Plate X

Some flowering trees: There are many trees which provide impressive displays of colour in the appropriate seasons when they are covered by a mantle of flowers which can be seen from afar. Special mention may be made here of a few of them by reason of the exceptional nature of such floral display. *Lagerstroemia flos reginae* bears great masses of magnificently coloured flowers. It appears in two varieties, in one of which the flowers have a rose-red colour, and in the other display a delicate purple hue. The spectra of the flowers exhibit the difference very conspicuously. The absorption in one case extinguishes the green sector of the spectrum, while in the other, the yellow sector is quenched. The spectra are reproduced in plate X.

Another magnificent flowering tree is *Jacaranda mimosifolia*, the beauty of the foliage of which is far excelled by the splendour of the flowers which the tree bears in profusion and which make it appear from a distance as if it were enveloped in a blue mist. Spectroscopic examination shows the origin of the colour of the flowers to be a weak absorption of the yellow sector in the wavelength range from 570 to 590 m μ and another weak absorption in the red sector from 630 to 640 m μ .

Amongst the numerous trees which display yellow flowers, special mention may be made of *Peltaphorum ferrugineum* by reason of the very striking nature of its display. As in the case of all yellow flowers, the colour has its origin in the extinction of the blue sector of the spectrum. The petals of the flowers of *Peltaphorum ferrugineum* are however very thin. As the result, the photographed spectra of the transmitted light exhibit the banded structure of the absorption spectrum of the pigments responsible for the colour.

CHAPTER XXI

The colours of gemstones

Colour plays a role of the highest importance in gemmology. Many gemstones display beautiful and characteristic hues and it is the precise shade and depth of that hue which determine the esteem with which a gem is regarded by its possessor. Since colour is what we perceive, it is evident that the characteristics of human vision would play a part in such perception which is no less important than the optical properties of the gemstone. It follows that the findings set forth in our earlier chapters are highly relevant in relation to the subject of gemmology. This will now be illustrated by reference to the behaviour of some gemstones studied by the author.

The green colour of emerald: The emerald has been held in high esteem in India since ancient times and great quantities of this gemstone were used in jewellery over many centuries. Quite recently, emeralds have been mined at various places in Rajaputana. A visit to Jaipur where the emeralds thus found are marketed enabled the author to obtain the material necessary for a study of the colour of this gemstone. The characteristic vivid green colour is exhibited by the hexagonal crystals of beryl of which emerald consists. Some of the material examined by the author consists of section-plates several mm thick cut normal to the optical axis and polished so that the spectrum of the transmitted light can be viewed directly. It is also possible to examine the spectrum of the light which passed through the specimen transversely to the optic axis. The depth of the colour varies considerably. Individual crystals may nearly be colourless and transparent. Deeply coloured specimens are also forthcoming.

It emerged from the studies that the perceived colour of emerald stands in the closest relationship to the extinction of the yellow sector of the spectrum in the wavelength range between 560 and 600 m μ . Such extinction is necessary for the green colour to manifest itself with that degree of saturation which is characteristic of the finest emeralds. The blue sector of the spectrum is also weakened, but it can still be perceived in the wavelength range between 450 and 500 m μ . The red sector in the wavelength range greater than 600 m μ is also much weakened but not totally extinguished. The residues left over of the red and blue sectors are masked from perception by the highly luminous green part of the spectrum.

The red rubies of Burma: The mines in the Mogok District of Upper Burma have been for many centuries the source of fine rubies which found their way to other

countries. The author is in possession of an ornament of sufficient age to be considered as an “antique” in which a group of these Burmese rubies have been inset with a gold plate at the back to reflect the light forwards and thus exhibit the colour of the stones to the best advantage. The spectral character of the red light thus shown up can be determined by simple inspection through a pocket spectroscope with a wavelength scale. It is found that there is a complete extinction of both the green and the yellow sectors of the spectrum, in other words, of the entire wavelength range from 500 to 600 $m\mu$. The red sector is present in full strength, and the part of the blue sector from 450 to 500 $m\mu$ also shows up quite clearly. It is evident that only the red of the spectrum is perceived and that the blue part which is actually present in the reflected light is completely masked from observation.

The blue sapphires of Ceylon: While on a short visit to Ceylon many years ago, the author was the recipient of a gift of material taken out during the working season from the gravel pits near Ratnapura which are the source of the far-famed gemstones of Ceylon. The material when sorted out and examined was found to include numerous pieces of corundum of varied colours. These were then separated from each other and kept apart for detailed study. Of particular interest were the specimens which showed a blue colour and could therefore be used to determine the spectral character of the light from blue sapphires. It emerged from the observations that the transmission through the material results in much reducing the brightness of the red, yellow and green sectors and particularly of the yellow, while on the other hand, the blue sector of the spectrum comes through without noticeable reduction of intensity. Thus, the explanation of the blue colour of the sapphires is that the light in the wavelength range from 500 to 700 $m\mu$ which is of diminished brightness is masked from perception by the light of shorter wavelengths.

A special mention may also be made of the corundum specimens exhibiting a purple hue which were found in the collection. This colour was much more evident when the light traversed the material in some directions than in others. The spectroscope revealed that the purple hue had its origin in a practically complete extinction of the yellow sector in the spectrum for the particular direction of transmission of light through the material. It may be remarked that these specimens when placed under an ultra-violet lamp exhibited luminescence of a red colour, whereas the blue sapphires were non-luminescent.

CHAPTER XXII

Dyes and textiles

The colouring of textile materials by the use of dye-stuffs is an art which dates back to the remotest antiquity. The development of synthetic dyes in great variety on the one hand and of new textile materials by chemical processes on the other hand has much enlarged the range of such activities. As a consequence, textiles form a group of man-made products exhibiting a great range of colours with which it is readily possible to obtain a deep insight into the relationship between the perceived colour and the spectral characteristics of the light reflected or diffused by the material.

Bangalore is well-known as a producer of dyed silk in a variety of colours to suit all tastes. A collection of thirty specimens covering a whole range of hues was procured for the study. A survey of this material furnishes useful illustrations of the basic principles of colour perception set forth in the preceding chapters. The observer has only to view through a pocket spectroscope, one after another, the whole series of samples after arranging them in some suitable order. The specimens should, of course, be examined in a good light. Indeed, the observations are best made with the specimens held in sunlight.

A purple-coloured silk included in the collection exhibited the dark band of extinction of the yellow sector in the spectrum which is characteristic of that hue. Another piece of silk which had a brilliant rose-red colour exhibited a practically complete extinction of the green sector, while the red and the blue sectors were in full strength and nearly the whole of the yellow sector was also present. Scarlet silk exhibited a nearly complete extinction of the yellow sector, while the green and blue sectors were barely visible in its spectrum. Silk which was of a full red colour showed a complete extinction of the yellow sector, while the green sector was barely visible and the blue sector was extinguished. Silk which was of a rich green colour showed the green sector of the spectrum brilliantly, while the yellow was scarcely visible and the blue and red sectors though very weak were clearly seen in the spectrum and were evidently masked from perception by the brilliant green sector.

Five of the silk pieces in the collection showed a sequence of colours ranging from a bright blue to a deep violet and a comparative study of their spectra was therefore of particular interest. A common feature of all the cases is that the entire spectrum is visible from end to end but with the red and yellow sectors much weakened. The great differences in the colour perceived in the sequence are not

consequential on any changes in the blue sector of the spectrum but arise from an alteration of the intensities in the green, yellow and red sectors. The progression of colour from bright blue to a darker blue and then to a very dark blue in three silks is the consequence of a progressive falling off in the luminosity of the green sector. The violet colour of the remaining two specimens results from the appearance of very conspicuous absorption bands in the orange-yellow region of the spectrum.

Four pieces of silk exhibited a regular colour sequence ranging from a pale yellow to a deep orange. The spectroscope showed a visible weakening of the blue sector to be the origin of the colour of the pale yellow silk. An extinction of the blue sector, an advance of the absorption further into the green sector and then the nearly complete absorption of the green sector represent the successive stages leading up to a deep orange as the colour of the silk.

Besides the specimen of a rich green colour mentioned above, there were several others which could also be listed as green but differed from it in respect of either colour or brightness or both. One of these specimens calling for special mention was quite brilliant but its colour could be more accurately described as a greenish-yellow. Its spectrum closely resembled that of the other green silks except that the presence of the yellow sector was readily recognisable. The specimen thus illustrates the very great influence which the yellow of the spectrum has on the colour and luminosity of composite light.

Several silks in the collection exhibited colours in which the presence of blue in association with the green could be recognised. Indeed, some could be listed as blue rather than as green. It is a noteworthy fact that in all such cases, the green sector of the spectrum appears far more luminous than the blue sector. It was possible, however, to recognise the progressive increase in the brightness of the blue sector with the change in the observed colour from a green to a greenish-blue.

CHAPTER XXIII

The reproduction of colour

As is well-known, the materials, processes and techniques which are made use of in colour photography are based on the three-colour principle. They assume that our visual perception of colour is a result of a superposition of the visual perceptions of the same field as seen through filters which transmit the parts of the spectrum appearing in the red, green and blue sectors respectively. The existence of the yellow sector of the spectrum as an independent origin for the sensations of light and colour is totally ignored. That this has not resulted in a complete failure of the processes which have been developed for the reproduction of colour obviously calls for explanation or elucidation. It is also evident that in certain circumstances, the techniques adopted would fail to reproduce the visually perceived effects. It is proposed in this chapter to consider both the successes and failures of colour photography based on the three-colour principle.

In an earlier chapter, reference has been made to the use of a filter of glass doped with neodymium oxide for the study of the interference colours of thin films. A small piece of such glass, 5×4 cm in area and 3 mm thick, is quite adequate for such observations. Held against a white background, it is observed to reduce its brightness very considerably and to exhibit a purplish hue in the transmitted light. These effects are due to the complete extinction of the part of the spectrum in the wavelength range from 570 to 600 m μ . There is no visible weakening of the red, green, and blue sectors of the spectrum, though a few faint bands of absorption can be seen in the green. The effect of the practically complete removal of the yellow from the spectrum by the filter is very strikingly exhibited when a highly luminous field, e.g., a sunlit white cloud or a part of the sky in the vicinity of the sun is viewed through the filter held in front of the eye. A surprisingly large reduction in the brightness of the area under view is noticeable. This is incidentally also an illustration of the increasingly important role played by the yellow sector of the spectrum at high levels of illumination.

The effects on the perceived colours produced by observation through the neodymium filter are very curious and interesting. The blue sky, for example, appears bluer, though a little less bright. The green grass on a lawn appears of a deeper green colour, and a similar effect is observed with the leaves of plants or trees which are of a light green hue. But there is no observable effect on the colour of leaves which are themselves dark green. The scarlet flowers of a geranium appear red as seen through the filter, and pale red or pink flowers appear of a

deeper red. The face of a fair-complexioned person appears suffused with blood when viewed through the filter. On the other hand, no change is perceivable with flowers or leaves of a bright yellow colour or in the cases of flowers or other objects which are themselves of a bright red or blue colour.

None of the foregoing statements would appear surprising in view of the findings recorded in the earlier chapters regarding colour in various cases. Generally speaking, it may be said that it is the absence of the yellow sector in the spectrum of composite light and not its presence which is significant and results in the perception of vivid colours such as purple, blue, green or red. Hence, processes for the reproduction of colour which take no account of the yellow sector do not suffer thereby and may actually gain in some cases. Some remark is necessary here regarding objects that exhibit a yellow colour in ordinary daylight. Such yellow is, in practically all cases, the result of an absorption of the blue sector of the spectrum, in other words, represents the integrated perception of all the other three sectors taken together, and not of the yellow sector alone. Hence, the exclusion of the yellow sector would result in a substantial reduction of intensity but not in any alteration of colour.

Colour photography based on the three-colour principle however fails to record what the eye perceives in the interference patterns such as those described and discussed in Chapters VII and XIX above when viewed by white light. The reason for this failure is that the variations in the brightness of the yellow sector of the spectrum due to interference determine the characters of the pattern both in respect of intensity and the distribution of colour. It is significant that the pictures in colour obtained of such patterns closely resemble what is seen of them when viewed by an observer through a filter of neodymium glass.

Colour reproduction by half-tone process: Some remarks may be usefully made here regarding the processes used for printing pictures in colour on paper with the aid of blocks in half-tone. It is customary to use four colours, viz., yellow, magenta, cyan and black. Usually, the first printing is with the yellow ink, the second printing is with the magenta ink, while the third printing is with the cyan ink. The fourth printing with black ink completes the picture which would otherwise fail to exhibit the local contrasts in respect of brightness exhibited by the object itself.

It should also be mentioned that the printing blocks are prepared by the half-tone process. The cross-line screen used in the process results in the breaking up of the picture into thousands of dots of light of varying size. These dots would appear in the impressions recorded on the paper by each of the four printing blocks. It should be emphasised that it is not the intention that the sets of dots in the impressions left by the four blocks should be coincident. On the other hand, to avoid such coincidence as far as possible, the half-tone screens are set at different angles to each other, these being so chosen as to avoid the appearance of moire patterns or other objectionable features in the reproductions. To secure these

results, it is sometimes found desirable to use a different screen-ruling for the yellow plate than for the plates of other colours.

If, in the picture as finally printed, the dots of different colours do not actually overlap, the eye is presented with a mosaic in which areas of white, black, yellow, magenta and cyan of varying sizes are interspersed. It would evidently be not possible for the eye to take note of their individual presence and the visual impression would therefore be a synthesis in which the effects of the individual areas are integrated into a single sensation. This sensation would depend on the relative proportions of the five areas exhibiting different colours. As the absorption spectra of the three coloured inks are very different, we may expect that a wide range of colours would be exhibited in various cases.

When photographic reproductions in colour are viewed through a magnifier, the structures which appear in them as areas of colour are immediately recognisable. In some cases, they exhibit hexagonal outlines, in others they appear as squares. The sizes of the individual dots and the colours which they show can readily be related to the colour exhibited to the eye by the entire group. Where the colour is yellow or blue-green or magenta, the dots of those colours are naturally predominant. In areas exhibiting other colours, the presence of dots of two or three different colours is evident and their influence on the perceived colour is readily traceable.

Summing up, we may say that when we view a photographic reproduction in colour, in general we perceive hues which are not really there, but represent a synthesis effected within the eye of the observer.

CHAPTER XXIV

Night-blindness

It has long been known that night-blindness or the inability to see properly at night is an affliction caused in some way by poor diet and that it may be cured by the consumption of certain food materials which were found by experience to be capable of remedying the deficiency. But night-blindness unconnected with malnutrition or disease is also known. The author became aware of a case of this kind, and the present chapter commences with a detailed study of the vision and visual characteristics of the person concerned who will be referred to here as Murthy, which is not his real name.

Murthy (age 26 years) is a young man in excellent health and apart from night-blindness is endowed with perfect vision, not needing any glasses either for near or for distant vision. He was examined by various tests for colour perception and for colour discrimination, and here again he was found to be perfectly normal. He was aware of his own disability since his earliest years and described it in some detail. Apart from its being congenital, the disability was also inherited, since his father had it during his lifetime, and one of his sisters at present experiences a similar disability.

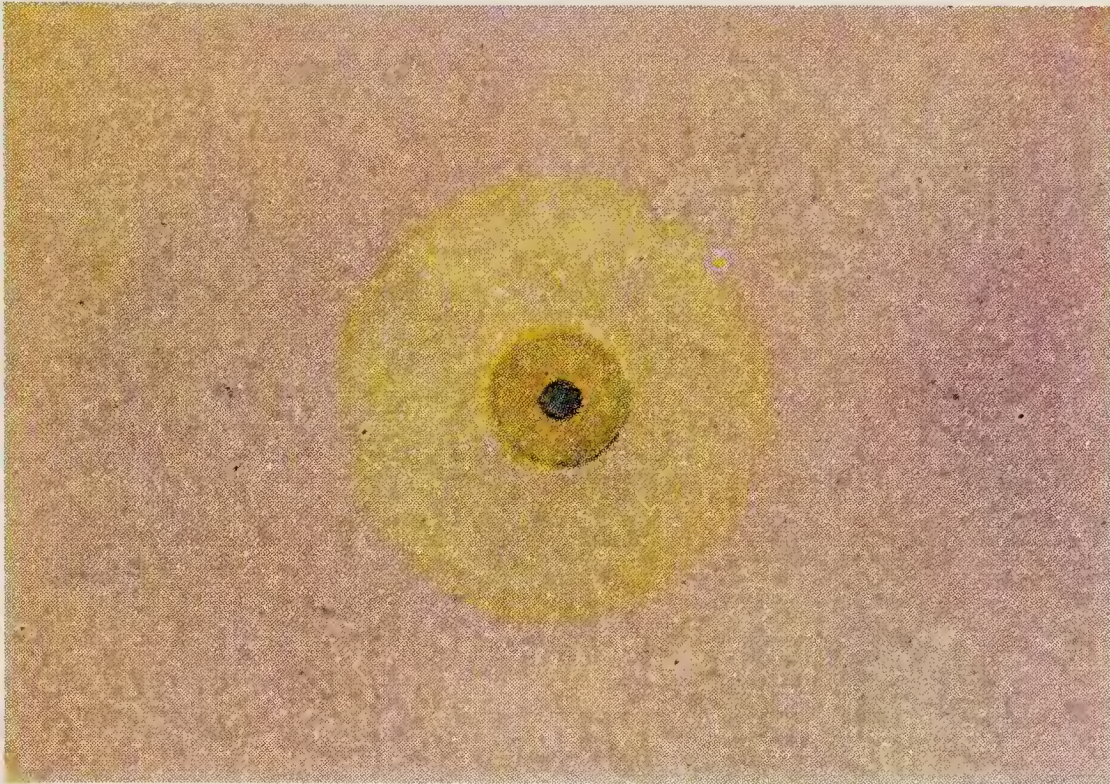
Murthy was tested for acuity of vision with the aid of an ophthalmic chart in a darkened room lighted by a window covered by an iris-diaphragm in the manner explained in earlier chapters. Seated at an appropriate distance from the chart, Murthy read off the successive rows of letters correctly and without hesitation in the same manner as a normal observer. This continued to be the case even at low levels of illumination so long as the letters could be read by a normal observer. The existence of a difference between Murthy and a normal observer became evident only at such low levels that a normal observer seated at the usual distance from the chart is unable to read the letters on it. At such levels, the chart continued to be visible to the normal observer but not to Murthy. A noteworthy effect is observed in these circumstances, viz., that when Murthy moved towards the chart and came close to it, the chart could be seen by him and appeared bright enough to permit of his reading the letters on it.

It appeared of interest to investigate whether Murthy differed from normal individuals in respect of his sensitivity to dim light in the central and peripheral regions of the retinae of his eyes. To test this, a uniformly illuminated screen which diffuses the light over a wide range of angles is employed. Such a screen appears brighter over its marginal regions than in the central areas, when the

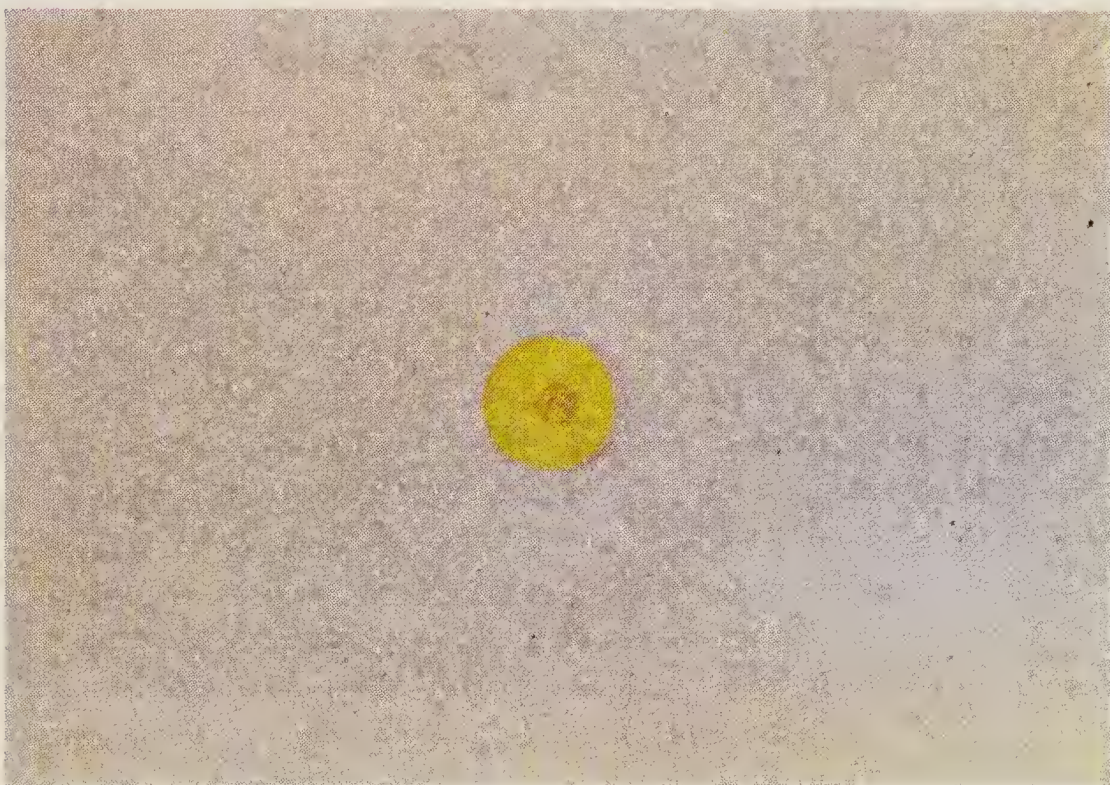
illumination is at low levels and the screen is viewed by an observer close to the screen. The phenomenon is noticeable when white light is employed, as also with monochromatic illumination. Its origin is evidently the greater sensitivity of the retina to dim light in its peripheral regions. Murthy's reports of what he saw of the phenomenon did not seem to indicate any differences between him and a normal observer.

Since Murthy's perception of colour is normal at ordinary or daylight levels of illumination, there was no reason to expect that it would exhibit any abnormalities at lower levels of brightness. The question was however carefully examined using the methods described in the earlier chapters of this book. No abnormality was disclosed by the investigation, and Murthy's sensory reactions to light in the different parts of the spectrum could be described as being identical with those of a normal observer, even in the dimmest light which he could perceive.

Since the inability of Murthy to perceive very dimly illuminated objects from a distance arises both in respect of foveal and of peripheral vision, it is clearly not possible to attribute it to any special features in the structure of his retinae, as for example, a deficiency in the proportion of rods to cones. It is also clearly not possible to attribute it to functional disorders of the kind arising from malnutrition. All the indications are that Murthy's defects of vision are a consequence of the inability of his eyes to transmit stimuli below a certain minimal strength to the centres of perception. Such inability arises also in the case of normal individuals whose eyes have been exposed to bright light, but only as a temporary phase. There seems to be a close similarity between the effects observed in the case of Murthy and those described in an earlier chapter on the adaptation of vision to dim light by normal individuals.



(3)



(4)

Figures 3 and 4. Views of the retina.

Plate III

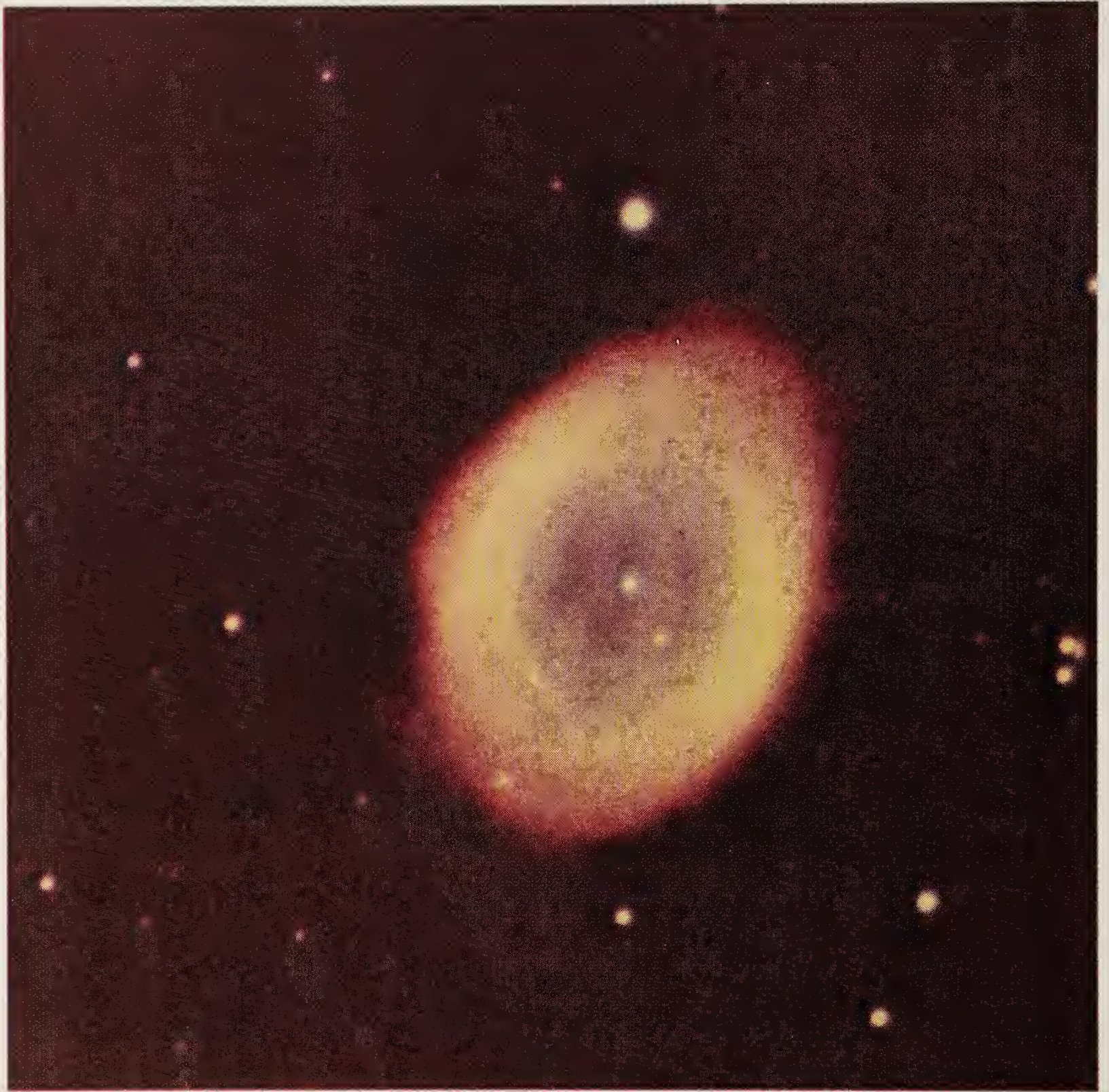
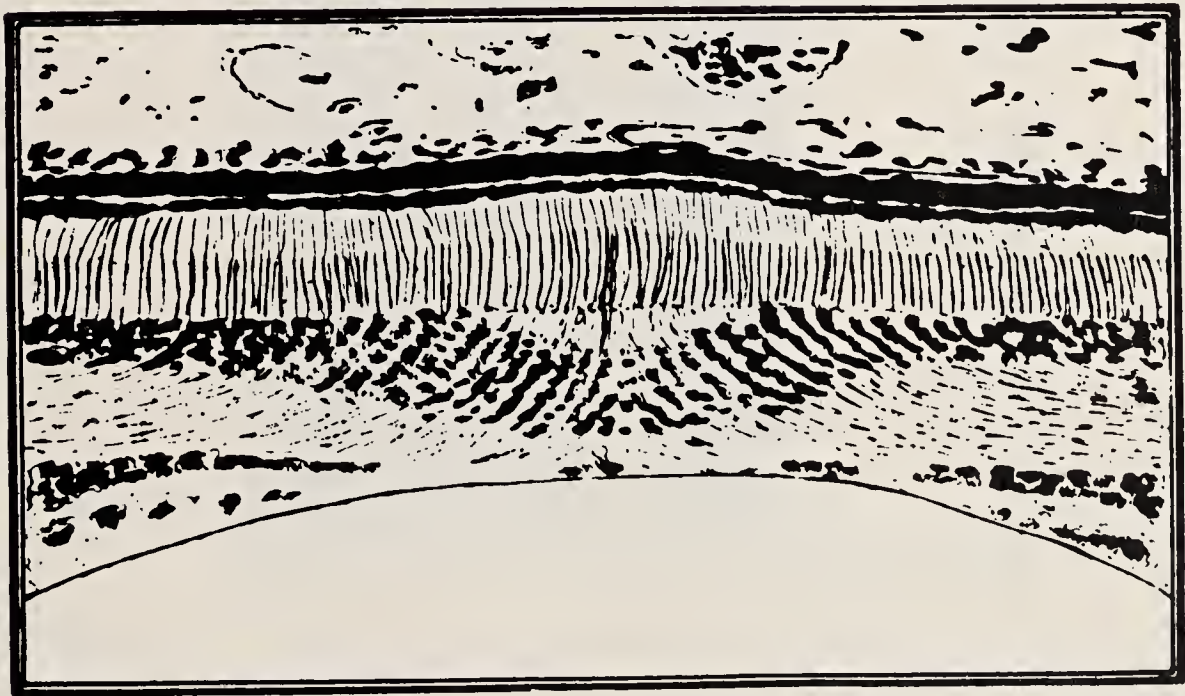
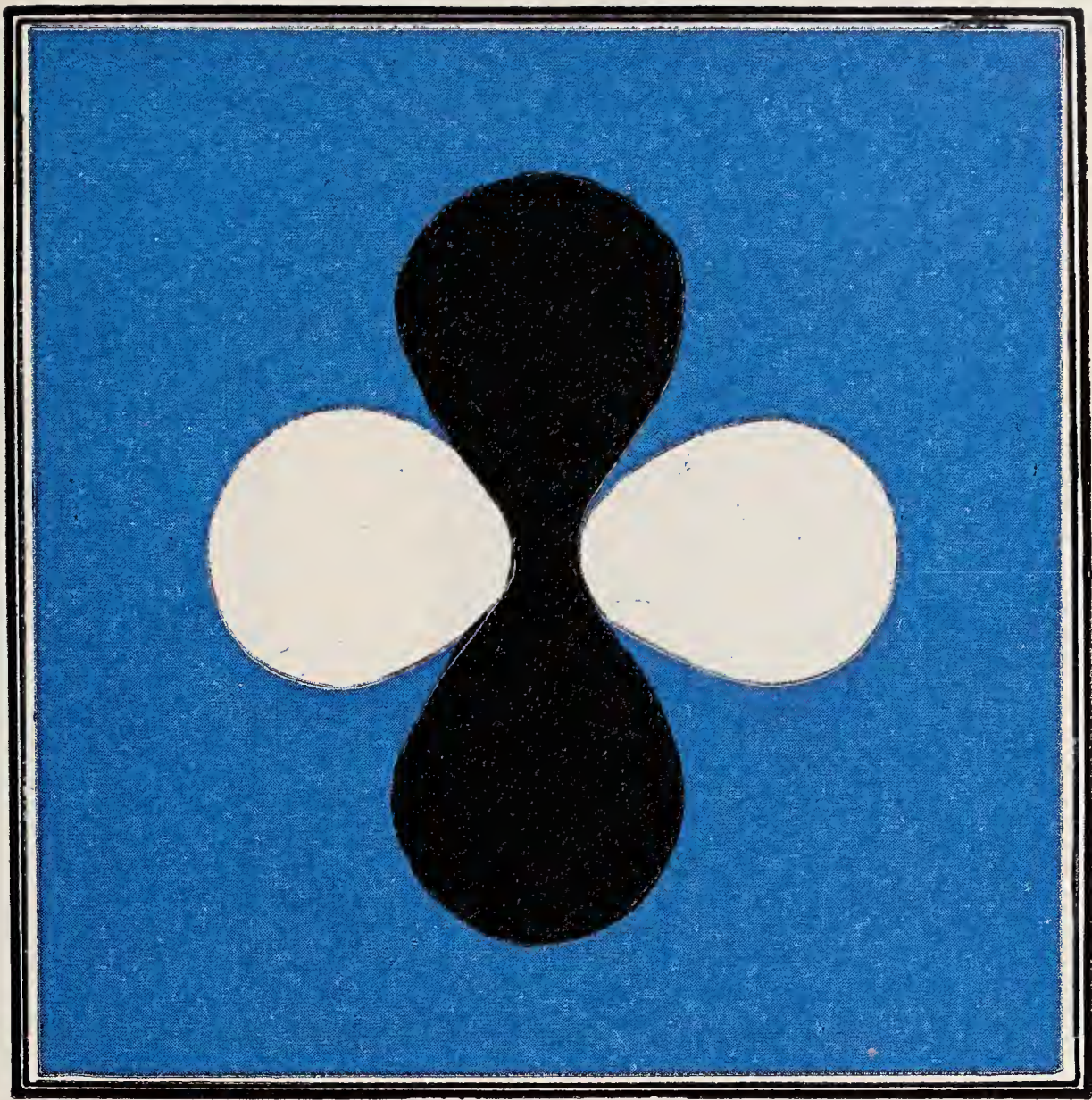
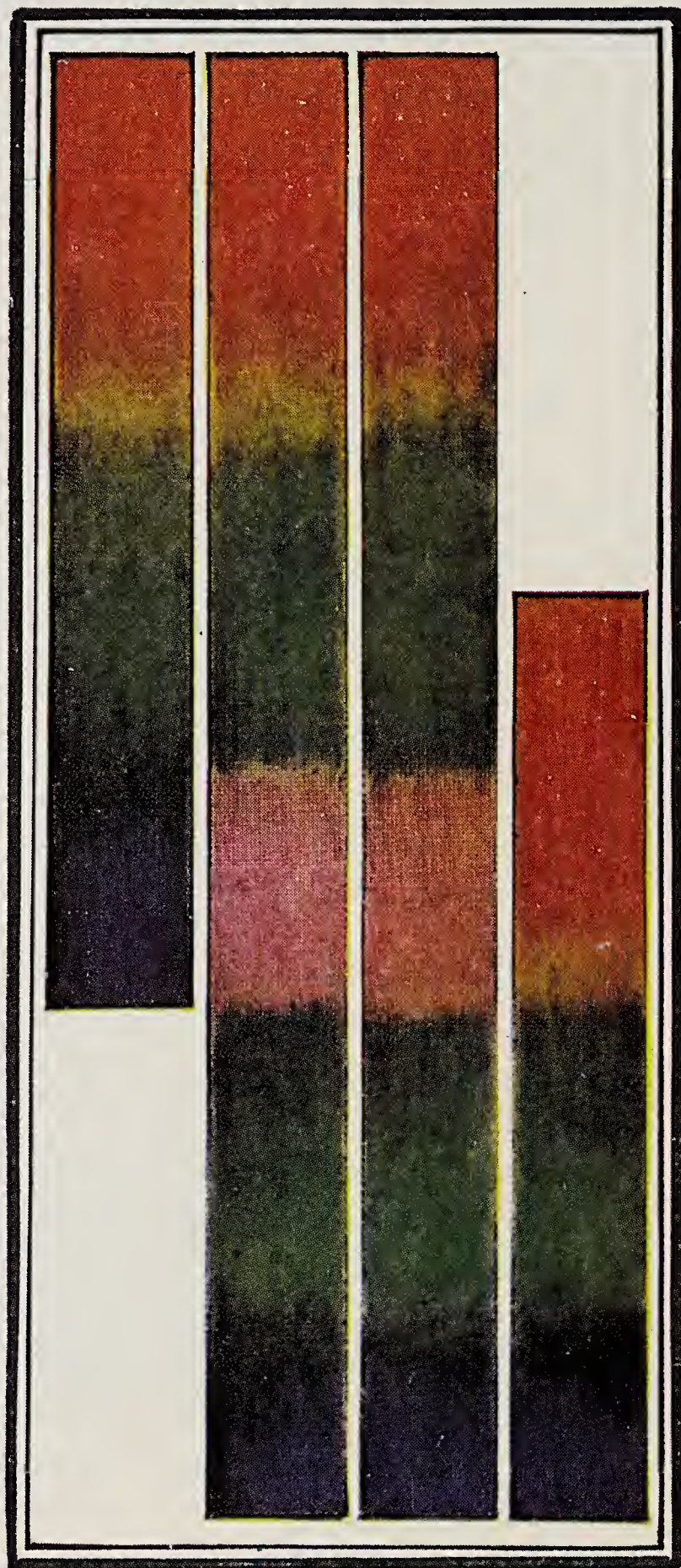


Plate IV. The ring nebula in lyra as seen in large telescopes.



Perception of polarised light and the structure of the fovea.

Plate V



The colours of superposed spectra.

Plate VI

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2. ON THE TRANSMISSION COLOURS OF SULPHUR SUSPENSIONS [1921 *Proc. R. Soc. London* **A100** 102; with B B Ray]
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217. SOME NEW METHODS IN KINEMATICAL THEORY [1912–13 *Bull. Calcutta Math. Soc.* **4** 1]
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293. REFLECTION OF X-RAYS WITH CHANGE OF FREQUENCY PART I. THEORETICAL DISCUSSION [1940 *Proc. Indian Acad. Sci.* **A11** 379; with P Nilakantan]
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296. QUANTUM THEORY OF X-RAY REFLECTION AND SCATTERING PART I. GEOMETRIC RELATIONS [1940 *Proc. Indian Acad. Sci.* **A12** 83; with N S Nagendra Nath]
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300. THE QUANTUM THEORY OF X-RAY REFLECTION: BASIC IDEAS [1941 *Proc. Indian Acad. Sci.* **A14** 317]
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- 305. NEW CONCEPTS OF THE SOLID STATE [1942 *Proc. Indian Acad. Sci.* **A15** 65]

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- 316. THE SCATTERING OF LIGHT IN CRYSTALS AND THE NATURE OF THEIR VIBRATION SPECTRA [1951 *Proc. Indian Acad. Sci.* **A34** 61]
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- 319. THE ELASTIC BEHAVIOUR OF ISOTROPIC SOLIDS [1955 *Proc. Indian Acad. Sci.* **A42** 1; with K S Viswanathan]
- 320. ON THE THEORY OF THE ELASTICITY OF CRYSTALS [1955 *Proc. Indian Acad. Sci.* **A42** 51; with K S Viswanathan]
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3. Floral colours

- 457. FLORAL COLOURS AND THEIR ORIGIN [1969 *Curr. Sci.* **38** 179]
- 458. THE FLORACHROMES: THEIR CONSTITUTION AND OPTICAL BEHAVIOUR [1969 *Curr. Sci.* **38** 451]
- 459. THE COLOURS OF ROSES [1969 *Curr. Sci.* **38** 503]
- 460. SPECTROPHOTOMETRY OF FLORAL EXTRACTS [1969 *Curr. Sci.* **38** 527]
- 461. BLUE DELPHINIUMS AND THE PURPLE BIGNONIA [1969 *Curr. Sci.* **38** 553]
- 462. THE VARIED COLOURS OF VERBENA [1969 *Curr. Sci.* **38** 579]
- 463. THE PELARGONIUMS [1970 *Curr. Sci.* **39** 1]
- 464. THE RED OLEANDER AND THE PURPLE PETRIA [1970 *Curr. Sci.* **39** 25]

4. Monograph—Physiology of Vision

- 465. THE PHYSIOLOGY OF VISION, Indian Academy of Sciences, Bangalore [1968 p. 1–164]

Raman deals with the possibility of a new type of twinkling of stars due to the statistics of photons striking the retina – and describes how to make these observations. Raman is amongst the earliest to set out in qualitative terms the presently accepted ideas on the conventional scintillation of stars as due to the corrugation of the incident wave front due to the atmosphere perturbation.

The book is full of simple experiments which can be set up and which illustrate many unforeseen aspects of the perception of light and colour.

